CS4090 Programming Project — Assignment

Responsible TAs: Janice van Dam (j.vandam-3@tudelft.nl)
Soubhadra Maiti (s.maiti-1@tudelft.nl) Bethany Davies (b.j.davies@tudelft.nl)

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1 Introduction

In this project you will investigate the performance of different distillation protocols in the presence of noise using a quantum network simulator. You will use this simulator to implement simulations of bipartite distillation schemes, collect data such as entangled state fidelity and protocol success probability by running your simulations for different noise regimes and write-up your conclusions in a report in the form of a research paper. In this document we lay out which distillation schemes you may consider (Section 2), introduce the simulator you will use (Section 3), give details on the expected structure of the paper you will write (Section 4) and explain the logistics of the project, such as group size, grading and relevant dates (Section 5).

2 Distillation Protocols

The list of distillation protocols you may implement is the following:

- DEJMPS [1]
- Extreme photon loss (EPL) [2, 3]
- BBPSSW [4]
- The protocol described in [5]

All of these protocols are bipartite distillation protocols. The first three were covered in class, and are $2 \to 1$ protocols, i.e. they take as input two entangled pairs and output, with some probability, one pair of higher fidelity. The fourth one, which is described in detail in the reference given, is a $3 \to 1$ protocol. How many protocols you should implement depends on the size of your group. This will be explained in detail in Section 5.

3 Simulation

In order to implement the above-listed protocols you will make use of NetQASM [6] and its software development kit (SDK). NetQASM is a low-level instruction set architecture for quantum networks under development at QuTech. Its SDK allows for a natural way of implementing quantum network applications, such as, but not limited to, distillation schemes, using Python. These applications will then be run on a quantum network simulator used as a backend, NetSquid [7], allowing for evaluation of their performance.

NetSquid is capable of simulating various realistic noise models. However, for simplicity, in this project you will make use of depolarizing noise only. More concretely, you will consider two sources of noise:

- Entangled state noise
- Gate noise

Let us now explain what is the effect of each of these sources of noise.

3.1 Entangled state noise

In order to perform distillation, the two nodes Alice and Bob must share entangled pairs. We assume that the states of these pairs are of Werner form:

$$\rho_{AB}(p) = p\,|\phi_{00}\rangle\langle\phi_{00}| + \frac{1-p}{4}\mathbb{I}_4, \tag{1}$$

where, as usual, $|\phi_{00}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ and $\mathbb{I}$ is the identity matrix. This corresponds to a perfect Bell state subject to a depolarizing channel of parameter p, meaning that we are modeling all the physical imperfections that may occur in the generation of an entangled pair as depolarizing noise.

3.2 Gate noise

The distillation schemes you will implement necessitate the application of gates, which in real-life are also noisy. As was introduced in Homework 2, one way of modeling this noise is by applying a perfect gate followed by a depolarizing channel. For a concrete example, imagine that we have a state $|\psi\rangle$ to which we want to apply a unitary U with depolarizing parameter p_U. The state after the perfect unitary is given by $|\psi\rangle_{\text{perf}} = U\,|\psi\rangle$. The state after the depolarizing channel (or, equivalently, after the noisy gate) is given by:

$$\rho_{\text{noisy}}(p_U) = (1-p_U)\,|\psi_{\text{perf}}\rangle\langle\psi_{\text{perf}}| + \frac{p_U}{2}\mathbb{I}_2. \tag{2}$$

The parameter p_U quantifies how noisy the gate is. $1 - p_U$ is known as the gate fidelity. $p_U = 0$ corresponds to a gate fidelity of 1, i.e. a perfect gate, whereas $p_U = 1$ corresponds to a gate fidelity of 0, i.e. a gate that destroys all information in the starting state, replacing it by a maximally mixed state.

3.3 Data gathering

Once you have implemented simulations of the distillation schemes, you will be able to run them for different values of the entangled state noise and gate fidelity and collect statistics on the final entangled state fidelity and distillation protocol success probability. NetSquid keeps track of the states in the simulation, allowing you to easily compute these quantities.

Instructions on how to install the required software are provided on Brightspace. A tutorial on programming using NetQASM's SDK was held in 2020, and the video of it can be found on Brightspace.

We note that the NetQASM and SquidASM packages are available publicly online (on GitHub). However, for this assignment we use specific (older) versions of these packages (the zip files on Brightspace) so that everyone can use the exact same code and our tutorial is still up to date.

4 Paper

The main goal of this project is an investigation of the performance of distillation protocols in the presence of noise, whose results you will write up in a report following the structure of a scientific paper. To do so, you must first identify the research question(s) you aim to answer. Some examples of possible research questions are:

- Considering perfect gates but noisy entangled states, does BBPSSW ever outperform DEJMPS?
- Assuming that the initial entangled fidelity is 0.9, what is the minimum gate fidelity that enables entanglement distillation using the EPL protocol?
- Which protocol allows for the highest final fidelity if the initial fidelity is 0.7 and the gate fidelity is 0.99? What if we vary the gate fidelity?

Note that this is by no means an exhaustive list, nor does it necessarily contain the most interesting questions to ask. It is instead meant only as a guideline for you to have an idea of what type of investigations you can conduct with the simulation tools you will implement. We encourage you to be creative and come up with your own research questions. Furthermore, there is also no hard and fast rule for how many research questions you should investigate. We leave this decision up to you, but be aware that of course a project that tackles only a single research question that e.g. ignores one of the noise sources cannot be graded as highly as a project that goes beyond that.

Your paper should roughly follow this structure:

- **Abstract**: A very short (roughly 250 words) summary of your paper. Feel free to check actual research papers for inspiration.
- **Introduction**: Here you explain why we are interested in studying entanglement distillation in the first place and introduce the protocols you implemented.
- **Research questions**: In this section you should introduce and motivate the research questions you aim to answer.
- **Results**: Having introduced the research question, you will present the data you collected to answer it. Examples of what might be present in this section include plots of final entangled state fidelity against gate fidelity for different protocols. Note that this is of course research question-dependent, so this example might not make sense in your case.
- **Conclusions**: Here you reflect on the results you obtained against the backdrop of your research question and, more broadly, the problem of entanglement distillation.
- **Bibliography**: This being a research paper, you should not forget to cite anything that was relevant to your work.

We expect the paper to be roughly 4 pages long, although this is not binding.

5 Logistics

5.1 Groups

We recommend that you work together in groups of up to 4 students. However, we understand that it might be hard to find a group. Therefore, we will also allow you to tackle the project individually if you prefer to. If you wish to the be in a group but do not know anyone to group up with, let us know and we will try to put people in this situation into groups. Feel free to start a new thread on Brightspace for this.

The number of distillation protocols to be implemented depends on the size of your group:

- 1 – 2 group members: 2 protocols
- 3 group members: 3 protocols
- 4 group members: 4 protocols

You will have freedom to choose which protocols you implement as long as you adhere to these guidelines. For example, a group of two students could choose to implement DEJMPS and BBPSSW.

5.2 Grading

The implementation of the protocols in code and the paper will be graded separately, with the final project grade being given by a weighted average of the two, 30% for the code and 70% for the paper. The criteria for the code will be correctness, i.e. does it produce the correct results. This will be tested by the TA team using the code that you submit. The paper will be graded based on the depth of the discussion of the results and the clarity of exposition.

5.3 What to Submit

You are expected to submit the paper write-up, in the form of a PDF file, and the application code, in the form of a compressed `.zip` archive. Only one student submits the project for the whole group.

Remember to list all the authors inside the PDF. The file name of the PDF must be:

```
LastNameStudent1_LastNameStudent2_...LastNameStudentN.pdf
```

The file name of the `.zip` archive must be:

```
LastNameStudent1_LastNameStudent2_...LastNameStudentN.zip
```

5.4 Important Dates

The tutorial from 2020 (video) is available on Brightspace and you can watch it right now. On Friday March 21st we will hold a similar tutorial in person. There will also be a question session for the project on Monday March 31st.

The deadline for the submission of the project is April 11th, 2025, at 23:59.

References

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[3] N. H. Nickerson, J. F. Fitzsimons, and S. C. Benjamin, "Freely scalable quantum technologies using cells of 5-to-50 qubits with very lossy and noisy photonic links," *Physical Review X*, vol. 4, no. 4, p. 041041, 2014.

[4] C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, and W. K. Wootters, "Purification of noisy entanglement and faithful teleportation via noisy channels," *Physical review letters*, vol. 76, no. 5, p. 722, 1996.

[5] D. P. Chi, T. Kim, and S. Lee, "Efficient three-to-one entanglement purification protocol," *Physics Letters A*, vol. 376, no. 3, pp. 143–146, 2012.

[6] A. Dahlberg, B. van der Vecht, C. Delle Donne, M. Skrzypczyk, I. te Raa, W. Kozlowski, and S. Wehner, "NetQASM-A low-level instruction set architecture for hybrid quantum-classical programs in a quantum internet," *Quantum Science and Technology*, 2022.

[7] T. Coopmans, R. Knegjens, A. Dahlberg, D. Maier, L. Nijsten, J. de Oliveira Filho, M. Papendrecht, J. Rabbie, F. Rozpędek, M. Skrzypczyk, *et al.*, "Netsquid, a network simulator for quantum information using discrete events," *Communications Physics*, vol. 4, no. 1, pp. 1–15, 2021.