

Master's Thesis (Academic Year 2023)

Link Management in Quantum Network

Keio University Graduate School of Media and Governance
Makoto Nakai

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Quantum networking is the new paradigm of networking that allows to transfer quantum state and achieve various new applications. RuleSet-based communication protocol is known to be one of the practical communication protocols to establish a scalable quantum network. Ideally, multiplexing and real-time resource management should be realized in order to improve the performance and robustness of the network. However, the protocol to handle multiple connections and allocate of physical links has not been proposed. This thesis proposes the link management protocol for quantum network that involves negotiation to determine a set of RuleSets (which is called a link allocation policy) to execute and the timing of apply the new link allocation policy. It also discusses the implementation of communication setup and teardown based on the proposed protocol and validates the proposed approach by performing a set of network simulations.

Keywords :

1. Quantum Networking, 2. RuleSet-Based Communication Protocol, 3. Networking Protocol,

Keio University Graduate School of Media and Governance
Makoto Nakai

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Chapter 1

Introduction

1.1 Background

The recent development of quantum technologies such as quantum computing, quantum networking and quantum sensing are expected to provide new capabilities. For example, quantum processors can theoretically simulate quantum systems whose size are intractable even for their classical equivalence [1]. Quantum network realizes the secure generation of an encryption key [2] [3]. Quantum sensing allows the detection of sensitive physical properties such as magnetic field.[4].

Also, various applications can be realized by connecting these technologies via quantum network, such as distributed quantum computing [5], blind quantum computing [6], a precise clock synchronization [7] and improvement of the resolution of telescopes [8]

However, there are two major problems for transmitting quantum data to a distance location. One is "non-cloning theorem" [9], which is the fact that quantum state cannot be copied. Unlike classical network, it is almost impossible to neither amplify a quantum state or send it forward because the quantum state will be heavily corrupted by the high probability of loss and high error rate. The other problem is that it is so difficult to establish a bell pair between nodes separated by a long distance, again due to a photon will be spoiled by the physical noise and photon loss.

These two problems can be solved by using particular type of nodes called quantum repeaters [10]. Quantum repeaters perform entanglement swapping [11] and purification [12], each of which extends two neighboring bell pairs to a single longer bell pair, and improves the fidelity of the bell pair, respectively. These operations end up with generating an end-to-end bell pair that can be used by quantum teleportation [13], which is the protocol to send an arbitrary quantum state to a distant location.

Entanglement swapping and purification involve requires frequent message exchange with neighboring nodes in order to coordinate actions, such as entanglement swapping and purification, with neighboring nodes and those communication slow down the generation of an end-to-end bell pair. However, a communication protocol [14] called RuleSet-based communication protocol solves this problem by distribute an object called RuleSet, which a sequence of operations execute to each node. This feature reduces the amount of unnecessary communication and improves the scalability of the entire network.

1.2 Research Contribution

Multiple connections should be established simultaneously in order to enhance the overall performance and robustness of the entire network and the same thing can be applied to quantum network. However, the previous work only proposes the method to allocate required physical bell pairs and establish a single end-to-end bell pair, in other word, an single connection by consuming those physical resources. This thesis proposes a protocol to realize three important tasks, which are the negotiation about what set of connections are going to be established, the one about when to switch from those in the previous round, and coordinated resource management between two nodes connected by each link. It also discusses the updated procedure of establishing a new connection and tearing down one of the existing connections while several connections are being established by applying the proposed protocol. The approach presented in this thesis is validated by the simulation of RuleSet-based quantum networks under several circumstances.

1.3 Thesis Structure

The structure of this thesis is as follows.

Chapter 2 provides the background knowledge to understand the key concepts readers would encounter throughout this thesis.

Chapter 3 explains the detail of RuleSet-based quantum networking.

Chapter 4 presents the problem that this thesis addresses.

Chapter 5 offers the overview of the link management protocol and the messages required for its negotiation process.

Chapter 6 provides how link management protocol proposed in this thesis will be triggered after the process of connection setup and teardown. It also includes the pseudocode of methods that the node software need to execute and messages outside of the link management protocol.

Chapter 7 presents several scenarios used to validate this protocol.

Chapter 8 offers the conclusion of this thesis and discusses future works.

Chapter 2

Background

2.1 Quantum Physics

This subsection provide the fundamental knowledge of quantum physics, which will make readers feel familiar with the concept and notations that they will encounter throughout this thesis.

2.1.1 Pure State

Pure state is the representation of quantum state of the whole system without the assumption of external noise.

Quantum Bit

A conventional computer uses a bit to represent a basic unit of information, which are 0 and 1. A basic unit of quantum information, on the other hand is called a quantum bit (or **qubit** in short) are $|0\rangle$ and $|1\rangle$, each of which can be described in the form of a vector.

For example

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

The state of a single qubit $|\psi\rangle$ can be described as follows.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (\alpha, \beta \in \mathbb{C}, |\alpha|^2 + |\beta|^2 = 1)$$

. After the operation called measurement, the quantum state would be collapsed into either 0 or 1. The measurement probability of 0 is $|\alpha|^2$ and that of 1 is $|\beta|^2$. In other words, a single qubit can take both states probabilistically at the same time.

For instance, a qubit can be

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle \tag{1}$$

whose measurement probability of 0 and 1 is 50% and 50% respectively.

Bloch Sphere

Because $|\alpha|^2 + |\beta|^2 = 1$, the notation of a single qubit state can be represented like this.

$$|\psi\rangle = e^{i\gamma} \left(\cos \frac{\theta}{2} + e^{i\phi} \sin \frac{\theta}{2} \right) (\gamma, \phi, \theta \in \mathbb{R}) \quad (2.1)$$

Because $e^{i\gamma}$ is just a global state, it can be ignored and the same state can be rewritten like this.

$$|\psi\rangle = \cos \frac{\theta}{2} + e^{i\phi} \sin \frac{\theta}{2} (\phi, \theta \in \mathbb{C}) \quad (2.2)$$

Because the equation above has two parameters, any pure single qubit state can be considered as a point on the surface and its geometric representation is called **Bloch sphere**.

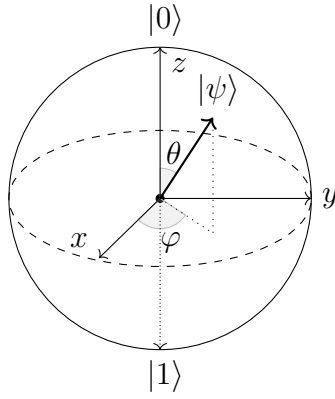


Figure 2.1: Bloch Sphere

Multi-Qubit State

The quantum state for multi-qubits is a **tensor product** of a state vector of each qubit. The general notation of two qubit state is

$$|\psi\rangle = (\alpha|0\rangle + \beta|1\rangle) \otimes (\gamma|0\rangle + \delta|1\rangle) \quad (2.3)$$

$$= \alpha\gamma|00\rangle + \alpha\delta|01\rangle + \beta\gamma|10\rangle + \beta\delta|11\rangle \quad (2.4)$$

$$(\alpha, \beta, \gamma, \delta \in \mathbb{C}, |\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1) \quad (2.5)$$

For example, the state $|00\rangle$ is equal to

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} \otimes \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2.6)$$

However, some quantum states such as

$$|\psi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle \quad (2.7)$$

cannot be decomposed into quantum state of each qubit. These special quantum states are called **entangled** states.

2.1.2 Mixed State

Mixed state is another representation of quantum state in more general cases, such as the presense of physical error. Mixed state is described in the form of a matrix which is called density matrix. Assume quantum system takes one of their collections $\{|\psi_i\rangle\}$ (i is an index) with the probability of p_i .

Mixed State

The density matrix of this system ρ is described by

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| \quad (2.8)$$

Evolution

The quantum system after applying a unitary operator U is the following.

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| \xrightarrow{U} \sum_i p_i U|\psi_i\rangle\langle\psi_i|U^\dagger \quad (2.9)$$

Measurement

Suppose one performs measurement on a quantum state $|\psi_i\rangle$ using a measurement operator M_m .

Then, the measurement probability of m is

$$p(m|i) = \langle\psi_i|M_m^\dagger M_m|\psi_i\rangle = \text{tr}(M_m^\dagger M_m|\psi_i\rangle\langle\psi_i|) \quad (2.10)$$

The measurement probability of m from the collection of state $\{|\psi_i\rangle\}$ is

$$\begin{aligned} p(m) &= \sum_i p_i p(m|i) \\ &= \sum_i p_i \langle\psi_i|M_m^\dagger M_m|\psi_i\rangle \\ &= \sum_i p_i \text{tr}(M_m^\dagger M_m|\psi_i\rangle\langle\psi_i|) \\ &= \text{tr}(M_m^\dagger M_m \rho) \end{aligned} \quad (2.11)$$

The quantum state after the measuring $|\psi_i\rangle$ is

$$|\psi_i^m\rangle = \frac{M_m|\psi_i^m\rangle}{\sqrt{\langle\psi_i^m|M_m^\dagger M_m|\psi_i^m\rangle}} \quad (2.12)$$

The corresponding density matrix is

$$\rho_m = \sum_i p(i|m) |\psi_i^m\rangle \langle\psi_i^m| = \sum_i p(i|m) \frac{M_m|\psi_i\rangle \langle\psi_i|M_m^\dagger}{\sqrt{\langle\psi_i^m|M_m^\dagger M_m|\psi_i^m\rangle}} \quad (2.13)$$

$$\begin{aligned} p(i|m) &= \frac{p(m,i)}{p(m)} = \frac{p(m|i)p_i}{p(m)} \\ &= \frac{\text{tr}(M_m^\dagger M_m \rho) p_i}{\text{tr}(M_m^\dagger M_m \rho)} \\ &= p_i \end{aligned} \quad (2.14)$$

Therefore, the state can also be described by the equation

$$\begin{aligned} \rho_m &= \sum_i p_i \frac{M_m|\psi_i\rangle \langle\psi_i|M_m^\dagger}{\text{tr}(M_m^\dagger M_m \rho)} \\ &= \frac{M_m \rho M_m^\dagger}{\text{tr}(M_m^\dagger M_m \rho)} \end{aligned} \quad (2.15)$$

2.1.3 Fidelity

Fidelity is one of the distance between two quantum state. the fidelity of quantum state ρ and σ is

$$F(\rho, \sigma) = \text{tr} \sqrt{\rho^{\frac{1}{2}} \sigma \rho^{\frac{1}{2}}} \quad (2.16)$$

For instance, if they commute and diagonal in the same basis like the following,

$$\rho = \sum_i r_i |i\rangle \langle i|, \sigma = \sum_i s_i |i\rangle \langle i| \quad (2.17)$$

The fidelity between these two states would be

$$\begin{aligned} F(\rho, \sigma) &= \text{tr} \sqrt{\sum_i r_i s_i |i\rangle \langle i|} \\ &= \text{tr} \left(\sum_i \sqrt{r_i s_i} |i\rangle \langle i| \right) \\ &= \sum_i \sqrt{r_i s_i} \end{aligned} \quad (2.18)$$

The fidelity between a pure state $|\psi\rangle$ and a mixed state ρ is

$$\begin{aligned} F(\psi, \rho) &= \text{tr} \sqrt{\langle\psi|\rho|\psi\rangle |\psi\rangle \langle\psi|} \\ &= \sqrt{\langle\psi|\rho|\psi\rangle} \end{aligned} \quad (2.19)$$

2.2 Quantum Operations

2.2.1 I Gate

I gate is equal to the 2×2 identity matrix, which is

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (2.20)$$

For example,

$$I|0\rangle = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle \quad (2.21)$$

$$I|1\rangle = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle \quad (2.22)$$

2.2.2 X Gate

X gate

X gate flips the logical value of a qubit.

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad (2.23)$$

For example,

$$X|0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle \quad (2.24)$$

$$X|1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle \quad (2.25)$$

2.2.3 Y Gate

Y gate flips the logical value of a qubit and add an imaginary number.

$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad (2.26)$$

For example,

$$Y|0\rangle = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ i \end{bmatrix} = i|1\rangle \quad (2.27)$$

$$Y|1\rangle = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -i \\ 0 \end{bmatrix} = -i|0\rangle \quad (2.28)$$

2.2.4 Z Gate

Z gate flips the phase of $|1\rangle$

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad (2.29)$$

For example,

$$Z|0\rangle = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle \quad (2.30)$$

$$Z|1\rangle = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \end{bmatrix} = -|1\rangle \quad (2.31)$$

2.2.5 H Gate

H gate creates superposition.

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (2.32)$$

For example,

$$H|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad (2.33)$$

$$H|1\rangle = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \quad (2.34)$$

2.2.6 Rotation Gate

2.2.7 General One Qubit Gate

2.2.8 Controlled-NOT Gate

A CNOT gate involves two qubits, one is called **controlled qubit** and the other is called **target qubit**. If the controlled qubit is 1, the bit value of the target qubit is flipped.

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (2.35)$$

For example,

$$CNOT_{0,1}|10\rangle = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = |11\rangle \quad (2.36)$$

$$CNOT_{0,1}|11\rangle = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = |10\rangle \quad (2.37)$$

2.2.9 Measurement

Quantum measurement can be described by using a group of measurement operators $\{M_m\}$ (m is the measurement result that is expected to get). If the quantum state before measurement is $|\psi\rangle$, the measurement probability of value m is

$$p(m) = \langle\psi|M_m^\dagger M_m|\psi\rangle$$

The quantum state after the measurement is

$$\frac{M_m|\psi\rangle}{\sqrt{\langle\psi|M_m^\dagger M_m|\psi\rangle}}$$

The measurement operators satisfy the completeness equation

$$\sum_m M_m^\dagger M_m = I$$

Also, the sum of the measurement probability of each possible measurement outcome is equal to one.

$$\sum_m p(m) = \langle\psi|\sum_m M_m^\dagger M_m|\psi\rangle = 1$$

2.3 Quantum Circuit

Here is the example of a quantum circuit.

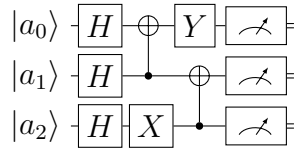


Figure 2.2: A example of quantum circuit

Each horizontal line represents each qubit and the square boxes that contain alphabets mean single quantum gates. The sign which involves a vertical line means a CNOT gate, and the box on the most right side indicates measurement.

2.4 Quantum Entanglement

Quantum entanglement is a special type of quantum state that cannot be described in the form of tensor product of the state of each particle.

2.4.1 Bell Pair

The entangled states between two qubits are called bell pairs, and each of four states has a special notation.

$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}} \quad (2.38)$$

$$|\Phi^-\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}} \quad (2.39)$$

$$|\Psi^+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}} \quad (2.40)$$

$$|\Psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}} \quad (2.41)$$

2.4.2 Multipartite Entanglement

There are cases that more than two qubits are entangled and that state is called Greenberger–Horne–Zeilinger state or GHZ state.

Here is the braket notation of the GHZ state that involves three qubits.

$$|GHZ\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}} \quad (2.42)$$

In the general case, the braket notation of the GHZ state of N qubits is the following.

$$|GHZ\rangle = \frac{|0\rangle^{\otimes N} + |1\rangle^{\otimes N}}{\sqrt{2}} \quad (2.43)$$

2.4.3 Bell State Measurement

Bell state measurement is a special type of quantum measurement that determines which bell pair the given two qubit entangled state is.

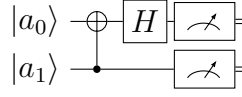


Figure 2.3: Quantum circuit for bell state measurement

Measurement results	Bell state
00	$ \Phi^+\rangle$
01	$ \Phi^-\rangle$
10	$ \Psi^+\rangle$
11	$ \Psi^-\rangle$

Table 2.1: A table of correspondence between measurement result and Bell pair

2.4.4 Quantum Teleportation

Unlike classical communication, quantum states cannot be just copied and transmit to other nodes due to the no-cloning theorem, which forbids duplication of any quantum state. However, a method called quantum teleportation was proposed, which overcomes the restriction and allows sender to transmit single qubit state to a distant location.

This method requires both the single qubit state and a new Bell pair, and also the sender have to prepare two qubits and the receiver have to prepare one qubit. After applying a CNOT gate and an H gate in the figure above, the sender have to measure both qubits and send those measurement results over the classical network. After the receiver get those measurement results and apply some quantum gates if the measurement results of corresponding qubits on the sender's side are 1, in order to correct on the quantum state on the receiver's side.

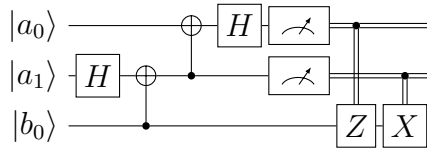


Figure 2.4: Quantum circuit for quantum teleportation

2.4.5 Entanglement Swapping

Entanglement swapping is the method to extend quantum entanglement by performing joint measurement on several quantum entanglement. For example, assume Alice has a single qubit, Bob has two qubits, and Charlie has one qubit. Then, there are Bell pairs between Alice's qubit and Bob's first qubit, and Bob's second qubit and Charlie's qubit, respectively. If Bob performs Bell state measurement on both of his qubits, Alice's qubit and Charlie's qubit are eventually entangled, even though they have not interacted with each other. This can be also seen as the teleportation of a Bell pair by sending one of its particles. Here is the figure of quantum circuit to perform entanglement swapping.

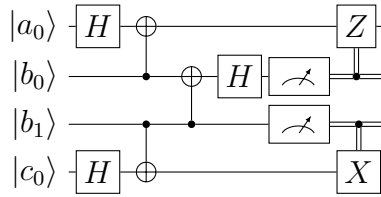


Figure 2.5: Quantum circuit for entanglement swapping

2.4.6 Entanglement Purification

Entanglement purification is a scheme to generate a set of quantum entanglements with higher fidelities from a larger set of imperfect quantum entanglements, local quantum operations, and classical communications. This procedure is also called entanglement distillation, or quantum concatenation. This section presents an example of entanglement purification that generates a single bell pair with higher fidelity from two of those with less fidelity.

Assume Alice and Bob are supposed to share $|\Phi^+\rangle$, which is one of the Bell pairs. However, the state would be converted to the following mixed state due to the noisy nature of a quantum channel.

$$\rho_{AB} = P_{\Phi^+}|\Phi^+\rangle\langle\Phi^+| + P_{\Phi^-}|\Phi^-\rangle\langle\Phi^-| + P_{\Psi^+}|\Psi^+\rangle\langle\Psi^+| + P_{\Psi^-}|\Psi^-\rangle\langle\Psi^-|$$

$$\sum_{s \in \{\Phi^+, \Phi^-, \Psi^+, \Psi^-\}} P_s = 1$$

Any mixed state can be converted to Werner state by applying Pauli operations and $\frac{\pi}{2}$ operations, so Alice and Bob can obtain the following state.

$$\rho'_{AB} = F|\Phi^+\rangle\langle\Phi^+| + \frac{1-F}{3}(|\Phi^-\rangle\langle\Phi^-| + |\Psi^+\rangle\langle\Psi^+| + |\Psi^-\rangle\langle\Psi^-|)$$

Two noisy bell pairs are required for entanglement purification. One of the bell pair $\rho'_{a_1 b_1}$ is called source bell pair, which may be purified, and the other one $\rho'_{a_2 b_2}$ is called target bell pair, which is going to be measured. Then, Alice and Bob perform CNOT operations between a_1 and a_2 , and b_1 and b_2 , respectively. After that, they measure a_2

and b_2 respectively, which is the qubit on the target bell pair on their side and exchange the measurement results. If their measurement results match, the purification is successful, while they have to discard the source bell pair and try again if those results do not match.

Here is the quantum state after measuring the target bell pair.

$$\rho'_{ab} = \frac{1}{N} \left[F^2 + \frac{1}{9}(1-F)^2 \right] |\Phi^+\rangle\langle\Phi^+| + \frac{2F(1-F)}{3N} |\Phi^-\rangle\langle\Phi^-| + \frac{2(1-F)^2}{9N} (|\Psi^+\rangle\langle\Psi^+| + |\Psi^-\rangle\langle\Psi^-|)$$

$$(N = F^2 + \frac{2F(1-F)}{3} + \frac{2(1-F)^2}{9})$$

The purification becomes successful if $F > \frac{1}{2}$. The readers can refer to more detailed calculation in the Appendix A.1

2.5 Quantum Networking

This section explains the important concepts of quantum networking.

2.5.1 Quantum Node

Quantum nodes are the nodes on a quantum network, which can be categorized into one of the following three categories, which was discussed in [15]

End nodes

MEAS measures the photons it receives. Although its functionality seems to be pretty limited, a pair of this node can perform quantum key distribution. In addition to that, the single node can be used as a terminal for blind quantum computation.

COMP represents quantum processor. This node also has the functionality of measuring qubits and also storing them in quantum memories.

SNS has sensing functionality by using quantum entanglement, which can be used for clock synchronization and a reference frame for interferometry.

Quantum repeaters and routers

REP1 plays a role of the 1st generation quantum repeater. It performs entanglement swapping and improves the fidelity of bell pair by purification. The detail of each generation of quantum repeater network will be discussed in the later section.

REP2 plays a role of the 2nd generation quantum repeater. It performs entanglement swapping and perform quantum error correction on a logical qubits, which is composed of several physical qubits.

RTR behaves as the border between two different networks and also involves rewriting the given RuleSets into either 1st generation protocol and 2nd generation protocol based on what the network assumes.

Support nodes

EPPS, which stands for an entangled photon pair source, performs symmetric parametric down conversion. It creates pairs of entangled photons and send them to link end points. This node is used in terrestrial links or in satellite, which emits photons to telescopes on the ground.

BSA or Bell State Analyzer, generates a entangled state between two quantum memories by swapping two different entanglements between a single quantum memory and a single photon. The success probability of entanglement swapping with linear optics scheme does not exceed 50%.

RGSS generates multipartite photonic entangled state for memoryless quantum network. It sends each half of the generated repeater graph state to the neighboring nodes. The photons are measured at link end nodes.

ABSA performs both a single-photon measurement and two-photon measurements and their measurement basis changes based on previous measurement outcomes, logical encoding and the structure of repeater graph states.

OSW plays a role of optical switches and can exist independently or as a part of the type of nodes that are mentioned above. It switches photons from incoming links to outgoing ones.

2.5.2 Quantum Link

Quantum link is a physical bell pair that is generated between two neighboring quantum nodes. This subsection introduces three link architectures discussed in [16].

MeetIntheMiddle

Meet-In-the-Middle, or MIM in short, collect photons from both end points of a physical link and create entanglements and send them back. Generation of these entanglements are performed in the Bell State Analyzer located in the middle.

SenderReceiver

Unlike MIM, the Bell State Analyzer is located in one of the endpoints of a physical link.

MidpointSource

EPPS in the middle performs generate entanglements and send them to the both endpoints of a physical link.

Chapter 3

Related Works

3.1 RuleSet-Based Quantum Network

3.2 Quantum Recursive Network Architecture

Chapter 4

Problem Definition

4.1 Problem Definition

In order to maximize the overall performance and the aggregative use of resource in the entire network, several connections are desired to be established in the real-time fashion. However, there are two major obstacles to overcome in the case of quantum network.

One is the absence of link management protocol for quantum network. There is a previous work [17] that proposes and compares the performance of various multiplexing strategies, but it does not mention any concrete methods to establish multiple connections and allocate the available physical links to each of these connections.

The other one is the lack of interaction between connection management and the subsequent resource management. The current RuleSet-based communication protocol [14] only proposes the scheme to establish a single connection and it does not explain the method to tear it down and free the allocated physical links after the end of RuleSet execution.

This thesis tackles the first problem by proposing the link management protocol the involves the negotiation about the set of connections to establish and the one about when to start the establishment. It also discuss the messages and their properties that are required to run this protocol.

Additionally, this thesis explains how the link management scheme is going to be triggered when a new connection is established and the old one is torn down. This explanation includes the methods to implement in the relevant software components when RuleSet-based quantum network is simulated or deployed in the real world.

Chapter 5

Proposal: Link Management For Quantum Network

5.1 Overview

This chapter proposes the protocol for the management of the physical bell pairs that are available on each quantum link.

This protocol has two separated phases. The first phase is the negotiation about the set of RuleSets that are going to be established in the next round. The second phase is the negotiation about when to apply the next set of RuleSets. These negotiations will take place between the two end point of each link.

5.2 Assumptions

This protocol is proposed based on the following assumptions.

- Existence of both a classical link and quantum link between two neighboring nodes.
- No delay in transmitting messages
- No failures in nodes and links
- Transmission of classical messages each of which includes a sequence number (an incremental identifier) from a support node every time a new bell pair is generated.

5.3 Requirements

This protocol has several requirements as follows.

Functional requirements

- The two end nodes of each link must coordinate what set of RuleSets and their order to execute in the next round

- The two end nodes of each link must coordinate the timing of when to execute these RuleSets

Non functional requirements

- This protocol must be adaptable to any link architecture assumed a quantum channel is based on.

5.4 Link Allocation Policy

5.5 The Negotiation About The Upcoming Link Allocation

5.6 The Negotiation About The Timing of Updating Link Allocation

5.7 Resource Allocation

5.8 Link Management Finite State Machines

5.9 Link Management Finite State Events

5.10 Type of Messages

5.11 Relationship With Connection Setup

5.12 Relationship With Connection Teardown

Chapter 6

Simulation

6.1 Overview of QuISP (Quantum Internet Simulation Package)

6.2 Major Components

6.3 BSA Controller

6.4 EPPS Controller

6.5 Bell Pair Store

6.6 RuleEngine

6.6.1 Link Allocation Policy Negotiation

6.6.2 Link Allocation Timing Negotiation

6.6.3 Resource Allocation

6.6.4 Connection Teardown

6.7 Connection Manager

6.7.1 LinkAllocationUpdateNotifier

6.7.2 Connection Teardown

Chapter 7

Evaluation

7.1 Experiment

7.1.1 Two Node Network With an MM Link

7.1.2 Two Node Network With an MIM Link

7.1.3 Two Node Network With an MSM Link

7.1.4 Two Node Network With an MIM Link (Without Timing Negotiation)

Chapter 8

Conclusion

8.1 Conclusion

8.2 Future Works

Appendix A

Appendix

A.1 The Entire Calculation To Derive The Bell Pair After Purification

Before applying a CNOT gate	After a applying CNOT gate
$ \Phi^+\rangle \Phi^+\rangle$	$ \Phi^+\rangle \Phi^+\rangle$
$ \Phi^+\rangle \Phi^-\rangle$	$ \Phi^-\rangle \Phi^-\rangle$
$ \Phi^+\rangle \Psi^+\rangle$	$ \Phi^+\rangle \Psi^+\rangle$
$ \Phi^+\rangle \Psi^-\rangle$	$ \Phi^-\rangle \Psi^-\rangle$
$ \Phi^-\rangle \Phi^+\rangle$	$ \Phi^-\rangle \Phi^+\rangle$
$ \Phi^-\rangle \Psi^-\rangle$	$ \Phi^+\rangle \Phi^-\rangle$
$ \Phi^-\rangle \Psi^+\rangle$	$ \Phi^-\rangle \Psi^+\rangle$
$ \Phi^-\rangle \Psi^-\rangle$	$ \Phi^+\rangle \Psi^-\rangle$
$ \Psi^+\rangle \Phi^+\rangle$	$ \Psi^+\rangle \Psi^+\rangle$
$ \Psi^+\rangle \Phi^-\rangle$	$ \Psi^+\rangle \Psi^-\rangle$
$ \Psi^+\rangle \Psi^+\rangle$	$ \Psi^+\rangle \Phi^+\rangle$
$ \Psi^+\rangle \Psi^-\rangle$	$ \Psi^+\rangle \Phi^-\rangle$
$ \Psi^-\rangle \Phi^+\rangle$	$ \Psi^-\rangle \Psi^+\rangle$
$ \Psi^-\rangle \Phi^-\rangle$	$ \Psi^-\rangle \Psi^-\rangle$
$ \Psi^-\rangle \Psi^+\rangle$	$ \Psi^-\rangle \Phi^+\rangle$
$ \Psi^-\rangle \Psi^-\rangle$	$ \Psi^-\rangle \Phi^-\rangle$

Table A.1: A table of correspondence between Bell pairs before and after applying a CNOT gate

Two noisy bell pairs are required for entanglement purification, so assume the quantum

state of the entire system can be described as follows.

$$\begin{aligned}
 \rho'_{a_1 b_1} \otimes \rho'_{a_2 b_2} = & F^2 |\Phi^+\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Phi^+| \\
 & + \frac{F(1-F)}{3} (|\Phi^+\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Phi^+| + |\Phi^+\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Phi^+| + |\Phi^+\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Phi^+| \\
 & + |\Phi^-\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Phi^-| + |\Psi^+\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Psi^+| + |\Psi^-\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Psi^-|) \\
 & + \frac{(1-F)^2}{9} (|\Phi^-\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Phi^-| + |\Phi^-\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Phi^-| + |\Phi^-\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Phi^-| \\
 & + |\Psi^+\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Psi^+| + |\Psi^+\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Psi^+| + |\Psi^+\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Psi^+| \\
 & + |\Psi^-\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Psi^-| + |\Psi^-\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Psi^-| + |\Psi^-\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Psi^-|)
 \end{aligned}$$

One of the bell pair $\rho'_{a_1 b_1}$ is called source bell pair, which may be purified, and the other one $\rho'_{a_2 b_2}$ is called target bell pair, which is going to be measured. Then, Alice and Bob perform CNOT operations between a_1 and a_2 , and b_1 and b_2 , respectively. The entire quantum state on this point would be as follows.

$$\begin{aligned}
 \rho'_{a_1 b_1} \otimes \rho'_{a_2 b_2} = & F^2 |\Phi^+\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Phi^+| \\
 & + \frac{F(1-F)}{3} (|\Phi^-\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Phi^-| + |\Phi^+\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Phi^+| + |\Phi^-\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Phi^-| \\
 & + |\Phi^-\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Phi^-| + |\Psi^+\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Psi^+| + |\Psi^-\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Psi^-|) \\
 & + \frac{(1-F)^2}{9} (|\Phi^+\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Phi^+| + |\Phi^-\rangle |\Psi^+\rangle \langle \Psi^+| \langle \Phi^-| + |\Phi^+\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Phi^+| \\
 & + |\Psi^+\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Psi^+| + |\Psi^-\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Psi^+| + |\Psi^+\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Psi^+| \\
 & + |\Psi^-\rangle |\Psi^-\rangle \langle \Psi^-| \langle \Psi^-| + |\Psi^-\rangle |\Phi^+\rangle \langle \Phi^+| \langle \Psi^-| + |\Psi^-\rangle |\Phi^-\rangle \langle \Phi^-| \langle \Psi^-|)
 \end{aligned}$$

Because getting the quantum state after measuring the last two qubits is equivalent to taking the partial trace of the target bell pair, here is the description of the source bell pair after measurement.

$$\begin{aligned}
 \rho'_{ab} = & \frac{1}{N} \left[F^2 + \frac{1}{9} (1-F)^2 \right] |\Phi^+\rangle \langle \Phi^+| + \frac{2F(1-F)}{3N} |\Phi^-\rangle \langle \Phi^-| + \frac{2(1-F)^2}{9N} (|\Psi^+\rangle \langle \Psi^+| + |\Psi^-\rangle \langle \Psi^-|) \\
 & (N = F^2 + \frac{2F(1-F)}{3} + \frac{2(1-F)^2}{9})
 \end{aligned}$$

The purification becomes successful if $F > \frac{1}{2}$

Acknowledgement

Reference

- [1] Richard P Feynman. Simulating physics with computers. *International journal of theoretical physics*, 21(6/7):467–488, 1982.
- [2] Charles H. Bennett and Gilles Brassard. Quantum cryptography: Public key distribution and coin tossing. *Theoretical Computer Science*, 560:7–11, Dec 2014.
- [3] Artur K. Ekert. Quantum cryptography based on bell’s theorem. *Phys. Rev. Lett.*, 67:661–663, Aug 1991.
- [4] I K Kominis, T W Kornack, J C Allred, and M V Romalis. A subfemtotesla multi-channel atomic magnetometer. *Nature*, 422(6932):596–9, Apr 2003.
- [5] Rodney Van Meter and Simon J. Devitt. The path to scalable distributed quantum computing. *Computer*, 49:31–42, 2016.
- [6] Pablo Arrighi and Louis Salvail. Blind quantum computation. *International Journal of Quantum Information*, 4(05):883–898, 2006.
- [7] Richard Jozsa, Daniel S Abrams, Jonathan P Dowling, and Colin P Williams. Quantum clock synchronization based on shared prior entanglement. *Physical Review Letters*, 85(9):2010, 2000.
- [8] E. T. Khabiboulline, J. Borregaard, K. De Greve, and M. D. Lukin. Optical interferometry with quantum networks. *Phys. Rev. Lett.*, 123:070504, Aug 2019.
- [9] A single quantum cannot be cloned. *Nature*, 299(5886):802–803, 1982.
- [10] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller. Quantum repeaters: The role of imperfect local operations in quantum communication. *Phys. Rev. Lett.*, 81:5932–5935, Dec 1998.
- [11] M. Żukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert. “event-ready-detectors” bell experiment via entanglement swapping. *Phys. Rev. Lett.*, 71:4287–4290, Dec 1993.
- [12] Charles H. Bennett, Herbert J. Bernstein, Sandu Popescu, and Benjamin Schumacher. Concentrating partial entanglement by local operations. *Phys. Rev. A*, 53:2046–2052, Apr 1996.

- [13] Charles H. Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres, and William K. Wootters. Teleporting an unknown quantum state via dual classical and einstein-podolsky-rosen channels. *Phys. Rev. Lett.*, 70:1895–1899, Mar 1993.
- [14] Takaaki Matsuo, Clément Durand, and Rodney Van Meter. Quantum link bootstrapping using a ruleset-based communication protocol. *Physical Review A*, 100(5):052320, 2019.
- [15] Rodney Van Meter, Ryosuke Satoh, Naphan Benchasattabuse, Kentaro Teramoto, Takaaki Matsuo, Michal Hajdušek, Takahiko Satoh, Shota Nagayama, and Shigeeya Suzuki. A quantum internet architecture. In *2022 IEEE International Conference on Quantum Computing and Engineering (QCE)*, pages 341–352. IEEE, 2022.
- [16] Cody Jones, Danny Kim, Matthew T Rakher, Paul G Kwiat, and Thaddeus D Ladd. Design and analysis of communication protocols for quantum repeater networks. *New Journal of Physics*, 18(8):083015, 2016.
- [17] Luciano Aparicio and Rodney Van Meter. Multiplexing schemes for quantum repeater networks. In *Quantum Communications and Quantum Imaging IX*, volume 8163, pages 59–70. SPIE, 2011.