Protocols for Packet Quantum Network Intercommunication

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ABSTRACT

A quantum network, which involves multiple parties pinging each other with quantum messages, could revolutionize communication, computing and basic sciences. A global system of various packet switching quantum and classical networks is called quantum internet, the internet in the future. To pave the way to the future quantum internet, unified protocols that support the distribution of quantum messages within the quantum internet are necessary.

Classical network functionalities, ranging from error-control mechanisms to overhead-control strategies, assume that classical information can be correctly read and copied. However, developing quantum internet protocols is more challenging since some classical techniques are forbidden by quantum effects, such as entanglement, measurement, and no-cloning.

In this paper, we investigate and propose protocols for packet quantum network intercommunication: quantum User Datagram Protocol (qUDP) and quantum Transmission Control Protocol (qTCP). To protect the fragile quantum information in the quantum internet, qTCP employs techniques of quantum error-correcting codes as well as classical techniques of stack design. In particular, the creation of the logical process-to-process connections of qTCP is accomplished by a quantum version of the three-way handshake protocol.

1 INTRODUCTION

The international race to build practical quantum computers is heating up. The US Congress recently passed the *National Quantum Initiative Act* to secure the leading position of U.S. in quantum computing. In the meantime, several grand quantum computing projects, which amount to billions of dollars, have been announced by China and the EU. Advances in quantum computing hardware have been very rapid over the past few years. Google, IBM, and Intel all announced their quantum chips of 72, 50, and 49 superconducting qubits (quantum bits), respectively, in 2018.

Modern computing and communication rest on the digital abstraction of information, measured in bits. A bit has a state either 0 or 1. Quantum mechanics allows a quantum bit (qubit) to be in a superposition of both states 0 and 1. In addition, the dimension of the state space grows exponentially with the number of qubits. These properties endow a quantum computer the power to achieve tasks that are beyond the capability of classical computers. For example, Grover's search algorithm [16], for querying an unsorted database on a quantum computer, affords a quadratic speedup when compared to its best classical competitor. Even more impressive is Shor's factoring algorithm [33], which provides an exponential speedup over the best known classical factoring approach. It is anticipated that "quantum supremacy" - the superiority of quantum computing over classical devices for a well-defined computational problem - will be achieved by NISQ (noisy intermediate scale quantum) devices in the near future [27]. All these phenomena indicate that we are in the transitions from studing quantum theory to engineering quantum information—the second quantum revolution [22].

An extraordinary quantum effect is entanglement— a strong quantum correlation between qubits that are even far apart. With preshared quantum entanglement between different parties, communication of quantum information can be done by so-called quantum teleportation [4]. Thus establishing entanglement attracts lots of attention [26]. A remarkable work is the system for long-distance and high-fidelity qubit teleportation developed by a team of researchers from Massachusetts Institute of Technology and Northwestern University in 2004 [21]. In 2018, deterministic delivery of remote entanglement on a quantum network was realized using diamond spin qubit nodes [17].

Being able to send qubits from one quantum processor to another allows them to form a quantum computing cluster. These quantum processors can together build an entangled qantum sytem. In this way several less powerful quantum processors are allowed to jointly perform more powerful tasks that are not possible with present-day technologies.

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This is often referred to as *networked quantum computing*, or *distributed quantum computing*, which may provide *exceptional* savings in communication complexity, compared with classical distributed computation (see, e.g., [28, 29] and the references therein). Therefore, networked quantum computing offers a path towards scalability for quantum computers, since more and more quantum processors can naturally be added to the network.

With several quantum networks joined together, the quantum internet would play an indubitable role in the development of the second quantum revolution. Besides the potential of exploring the computational power of quantum mechanics, the quantum internet could help to build ultrasharp telescopes [15], remote quantum computers and secure cloud quantum computing [6, 7, 23]. Immediately, the quantum internet would provide unparalleled capabilities that are provably impossible by only classical computation. For example, in 1984, Bennett and Brassard introduced the first and the most famous application of quantum internet, quantum key distribution (QKD) [2, 3], which enables two remote end nodes to establish provably-secure random keys. To implement quantum key distribution, it is sufficient for the quantum processors to be capable of preparing and measuring only a single qubit at a time. Many research teams have succeeded in building and operating quantum cryptographic devices since last century. In [14], the world's first network, the DARPA Quantum Network, was built, which delivers end to end network security via high-speed QKD by BBN, Harvard, and Boston University. Building the 1,200mile quantum communication landline between Beijing and Shanghai in 2016 and the quantum communication satellite (known as Micius) in 2017, China has the world's first space-ground quantum network [40].

Rapid experimental progress in recent years has brought first rudimentary quantum networks within reach. Physicists can control and manipulate quantum signals much better than before [20, 30]. In 2018, an idea is illustrated to store quantum information for hours at a time using special diamonds [1]. This makes the quantum information even more stable than the conventional information stored in the working memory of our computers. A team at Delft has already started to build the first genuine quantum network, which will link four cities in the Netherlands. Chicago Quantum Exchange, a research hub that is building a 30-mile quantum teleportation network using telecommunication fibers. It is likely that we will see the birth of the first multi-node quantum network in the next few years.

Very recently, the design of the quantum internet received much attention from an engineering communication perspective. Many challenges are formulated in [8, 9]. In a recent seminal work [36], Wehner and coauthors have drawn a road map for the future quantum internet. They proposed stages of development toward a full-blown quantum internet and highlighted experimental and theoretical progress needed to achieve them. Referring to the development history of the classical internet, the next step toward quantum internet is to estabilish a methodology of unified, reliable, ordered, and error-checked delivery of a stream of qubits between applications running on quantum endnodes. In particular, packet switching is a technique for reliably and efficiently transmitting data over a communication channel. A similar feature for quantum communication is desired. Thus we will imitate this packet switching technique and propose the quantum analogue for the quantum internet.

Moreover, Transmission Control Protocol/Internet Protocol (TCP/IP), developed by Vinton Cerf and Bob Kahn in [35], is one of the core components of the Internet that solves the previously mentioned problems in classical internet. TCP/IP provide a systematic classification of tasks that allows the different types of information processing to be accomplished by specific systems using the least amount of digesting of information, and thus enable the widespread use and applications of the classical internet. Almost all operating systems in use today, including all consumer-targeted systems, adopt a TCP/IP implementation. Therefore a unified protocol that allows quantum computers on different platforms to interconnect would be of extremely convenient, especially that there are different ideas of building quantum computers: superconducting qubits led by IBM and Google, ion trap led by the University of Maryland, topological qubits led by Microsoft, and so on. Unfortunately, such a network stack for quantum internet has not been presented yet but only some basic elements have been noted [24].

The frames of classical TCP/IP cannot be directly applied in the quantum network because of the significant difference between classical bits and quantum bits. Retransmission is one of the basic mechanisms used by protocols operating over a packet switched computer network to provide reliable communication (such as that provided by a reliable byte stream, for example TCP). However, retransmission is generally impossible for transmitting qubits due to the no-cloning theorem as we mentioned before.

In this paper, we investigate and propose protocols for packet quantum network intercommunication: quantum User Datagram Protocol (qUDP) and quantum Transmission Control Protocol (qTCP). The qTCP provides reliable, ordered, flow-controlled transmission of packets over the interlinked networks. To protect the fragile quantum information in the quantum internet, qTCP employs techniques of quantum error-correcting codes, *quantum secret sharing*, as well as classical techniques of stack design. In particular, the creation of the logical process-to-process connections of qTCP is accomplished by a quantum version of the *three-way hand-shake protocol*.

This paper is organized as follows. In Section 2, we introduce the basics of quantum mechanics. In Section 3, two models of quantum internet are given: repeater-based model and plain model. In Section 4, we discuss the main difficulties in designing quantum packet switching for quantum internet. In Section 5, a four-layer model of quantum network is shown. In Section 6, the four layers for the repeater-based quantum internet are given in detail, including the qUDP, qTCP protocols with the quantum three-way handshake protocol and similarly the four layers for plain quantum network are given in Section 7. Finally, in Section 8, we conclude with some highlighted research.

2 PRELIMINARIES

Here we present the bare-bones of quantum mechanics for our purpose. For more details, interested readers are referred to [25]. We start with the postulates of quantum mechanics.

2.1 State space

The state space of a closed quantum system is a complex Hilbert space and a *pure* quantum state is an arbitrary unit vector in the Hilbert space. In particular, a qubit system has a two-dimensional vector space with an orthonormal basis $\{|0\rangle,|1\rangle\}$. Thus the system can be in an arbitrary superposition of these two states, say $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$, where α and β are complex numbers satisfying the normalization condition $|\alpha|^2+|\beta|^2=1$. The dimension of the quantum system grows exponentially with the number of qubits: an n-qubit system has a 2^n -dimensional complex linear space with an orthonormal basis $\{|i_1i_2\cdots i_n\rangle\triangleq|i_1\rangle\otimes\cdots\otimes|i_n\rangle:i_j\in\{0,1\}\}$ and an n-qubit (pure) state can be an arbitrary superposition of these 2^n states. Note that \otimes is the tensor product and will be omitted with no ambiguity.

More generally, a quantum state can be represented by a density operator ρ , which is positive semi-definite and has trace equal to one. For a pure quantum state $|\psi\rangle$, its density operator is $|\psi\rangle\langle\psi|$. Quantum mechanics allows the quantum system in a more complicated state: a *mixed* quantum state, which is a convex combination of some pure states $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$ such that $p_i \geq 0$ and $\sum_i p_i = 1$.

2.2 Quantum evolution

The evolution of a closed quantum system can be described by a *unitary* transformation. An operator U is unitary if $U^{\dagger}U = UU^{\dagger} = I$, where U^{\dagger} is the complex conjugate transpose of U, and I is the identity operator. Suppose initially the system is in $|\psi_0\rangle$ and it evovles to $|\psi\rangle$ after time t. Then there exists a unitary U such that $|\psi\rangle = U|\psi_0\rangle$. A basis for the linear operators on a qubit is the Pauli matrices

$$I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, Y = iXZ.$$

A general quantum operation, usually denoted by \mathcal{E} , is a completely positive linear map, which preserves the trace.

2.3 Quantum measurement

A quantum measurement on a system is described by a collection of measurement operators $\{M_m\}$, which satisfy $\sum_m M_m^\dagger M_m = I$, and the index m stands for the measurement outcome. If a quantum system in the state $|\psi\rangle$ is measured, the probability that outcome m occurs is $p(m) = \langle \psi | M_m^\dagger M_m | \psi \rangle$ and the post-measurement state is $|\psi_m\rangle = \frac{M_m |\psi\rangle}{\sqrt{p(m)}}$. We can also describe the behavior of quantum measurement in the language of density operators. If ρ is measured by $\{M_m\}$, then the probability that outcome m occurs is $p(m) = \operatorname{tr}(M_m^\dagger M_m \rho)$, and the post-measurement state is $\rho_m = \frac{M_m \rho M_m^\dagger}{p(m)}$.

Next we introduce the effects of quantum teleportation, entanglement swapping, the no-cloning theorem, and quantum error correction.

2.4 Entanglement

A two-qubit pure state is entangled if they cannot be described by two independent single-qubit states. This, unlike the behavior of two correlated random bits, is a thoroughly non-classical behavior. Entanglement leads to non-local correlations, which seem to violate causality, so that Einstein, Podolsky, and Rosen mistakenly suggested that quantum mechanics might not be complete [13]. The state $|\Phi^+\rangle_{AB}=\frac{|0\rangle_A|0\rangle_B+|1\rangle_A|1\rangle_B}{\sqrt{2}}$ is called the maximally-entangled state, or simply EPR, where the subscript AB means that it is shared between A and B. We usually use $|ij\rangle_{AB}$ to denote $|i\rangle_A|j\rangle_B$.

2.5 Quantum teleportation

Quantum teleportation [4] is arguably the most famous quantum communication protocol. With the help of pre-shared entanglement between the sender and the receiver, quantum information can be transmitted from one location to another using only classical communication.

The teleportation protocol is as follows. Suppose Alice and Bob share an EPR pair $|\Phi^+\rangle_{AB} = \frac{|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B}{\sqrt{2}}$ and Alice wants to send to Bob an unknown qubit $|\psi\rangle_C = \alpha|0\rangle_C + \beta|1\rangle_C$. She performs a *Bell measurement* $\{M_{ij}\}$ on her two qubits AC, where

$$M_{ij} = |\Phi_{ij}\rangle_{AC}\langle\Phi_{ij}|_{AC}, \quad |\Phi_{ij}\rangle \triangleq (I_2 \otimes X^i Z^j)|\Phi^+\rangle$$

for $i, j \in \{0, 1\}$. Alice then sends Bob her measurement outcome $ij \in \{00, 01, 10, 11\}$. Interestingly, this two-bit message contains all the information that Bob needs to recover $|\psi\rangle$

on his side. To see this, observe that

$$|\Psi\rangle_C\otimes|\Phi^+\rangle_{AB}=\frac{1}{2}\sum_{i,j\in\{0,1\}}|\Phi_{ij}\rangle_{AC}\otimes\left(X^iZ^j|\psi\rangle\right).$$

According to Alice's measurement outcome ij, Bob's qubit will be in the state $X^i Z^j | \psi \rangle$ and thus $| \psi \rangle$ can be recovered after a *Pauli correction* $X^i Z^j$ on Bob's qubit.

To sum up, with the help of an EPR pair, the transmission of two classical bits is enough to transmit one qubit. Thus, one can transmit n qubits by transmitting 2n classical bits using n pre-shared EPR pairs.

2.6 Entanglement swapping

Suppose that Alice and Bob share an EPR pair $|\Phi^+\rangle_{AB_1}$, and Bob and Charlie share another EPR pair $|\Phi^+\rangle_{B_2C}$. It is possible to construct an EPR pair shared between Alice and Charlie by so-called *entanglement swapping*.

The procedure is as follows: Bob performs a Bell measurement on Bob's two qubits and sends the two-bit outcome to Charlie, who then performs a Pauli correction according to Bob's measurement outcome.

This can also be regarded as Bob teleporting his particle B_1 to Charlie by consuming the ERP pair $|\Phi^+\rangle_{B_2C}$. In other words, quantum correlations can be teleported.

2.7 No-cloning theorem

A fundamental property of quantum mechanics is that learning an unknown quantum state from a given specimen would disturb its state [5]. In particular, the quantum no-cloning theorem [12, 38] states that an arbitrary unknown quantum state cannot be cloned. Generally speaking, there is no quantum operation that can transform an unknown quantum state $|\psi\rangle\otimes|0\rangle$ into $|\psi\rangle\otimes|\psi\rangle$. Intuitively, this is because a quantum operation is always linear, while the desired mapping is not.

2.8 Quantum error correction

Qubits are maddeningly error-prone. A quantum error correcting code, first proposed by Shor [32], can protect quantum information against decoherence.

A noise channel is modeled as a quantum operation $\mathcal N.$ If there exist encoding and decoding quantum operations $\mathcal E$ and $\mathcal D$ such that

$$(\mathcal{D} \circ \mathcal{N} \circ \mathcal{E})(\rho) \propto \rho$$

for any input state ρ , we say that \mathcal{E} and \mathcal{D} correct the error of \mathcal{N} . That is, any quantum information encoded by \mathcal{E} can be perfectly recovered from the noise process \mathcal{N} by applying the recovering map \mathcal{D} .

One can observe the very useful fact that quantum errorcorrecting codes can correct errors coherently in the following sense. For encoding, noise and decoding operations

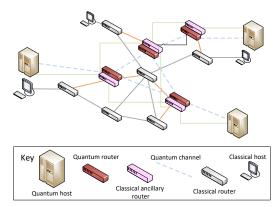


Figure 1: Quantum Internet.

 \mathcal{E} , \mathcal{N} , \mathcal{D} on A, $I_B \otimes \mathcal{E}_A$ and $I_B \otimes \mathcal{D}_A$ can correct the noise $I_B \otimes \mathcal{N}_A$ for any quantum system B.

3 QUANTUM INTERNET MODELS

The Internet is the largest engineered system ever created by mankind. With new quantum computing power, it can be further supplemented to form a more powerful internet—the quantum internet.

Figure 1 illustrates the concept of a quantum network, where several quantum computers are distributed and connected along with a classical network. *PCs*, *workstations*, *Web servers*, quantum computers, etc, are called *hosts*, or *endnodes*. Endnodes are connected together by a network of *communication links* and *routers*.

Here we discuss two models for the quantum internet: repeater-based model and plain model, assuming that two neighboring quantum devices share EPR pairs for teleportation or they are directly connected by quantum channels, respectively. These are natural generalizations of the Cleve-Buhrman model [10] and the Yao model [39] for twoparty quantum communication, where in the Cleve-Buhrman model quantum communication is done by teleportation with shared entanglement and classical communication, while in the Yao model qubit channels are used. (Note that repeater quantum networks have been discussed in the literature but there is no specification about how teleportation is done explicitly.) We further assume that all the nodes within the quantum internet can communicate classically, for example, over the classical internet, in order to exchange control information (such as the measurement outcome for Pauli correction in teleportation).

We emphasize that both our models features *full-duplex* data transmission as in the classical internet. In other words, (quantum or classical) data can be transmitted in both directions on a signal carrier at the same time.

In this paper, we only discuss the transmission of quantum information through the internet. Therefore, we will focus on the sub-network consisting of routers, hosts with

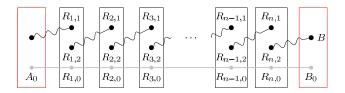


Figure 2: A repeater-based quantum channel. The gray lines are classical channels. Two entangled nodes are connected by a wavy line.

the power of quantum information processing, the quantum communication links and its corresponding classical communication links. This can be done by associate one-bit index with the IP for which host or router with quantum power.

3.1 Repeater-based Quantum Internet

A quantum channel between two neighboring quantum devices is required for the transmission of qubits. However, quantum channels are inherently lossy and they are not reliable for long-distance communication. Consequently, the techniques of *quantum repeaters* are used as intermediate nodes to reach long distances [18, 31, 34, 37].

The idea is to do a sequence of entanglement swapping or teleportation between two consecutive nodes so that quantum communication between two endnodes can be implemented as shown in Fig. 5. Suppose two neighboring nodes A and B are connected by repeaters R_1, \ldots, R_n , each of which has two (or more) qubits. EPR pairs are constantly created between repeaters $R_{i,2}$ and $R_{i+1,1}$ for $i=1,\ldots,n-1$, and between A and $R_{1,1}$, B and $R_{n,2}$. Then each repeater performs a Bell measurement on its two qubits and passes the measurement outcomes to B for Pauli correction, using classical channels (the gray lines in Fig. 5). This will create an EPR pair between A and B and thus full-duplex quantum communication can be implemented.

One may establish end-to-end EPR pairs at the beginning and then only classical communication remains to be done for quantum communication. But, in this way, the quantum buffer of the receiver will be occupied during stage of the classical communication. Thus we keep the flexibility that the entanglement swapping or teleportation is done when necessary. Another issue is the time cost. In order to transmit one qubit information from endnodes A to B using an endto-end EPR pair, the time cost is roughly the time cost of establishing an EPR pair between A and B, given EPR pairs between neighboring nodes are available, plus the time cost of transmitting two classical bits from A to B to accomplish the teleportation. If the path consists of n-1 repeaters, the time cost of establish an end-to-end EPR pair is roughly the transmission time for transmitting two bits for Pauli correction through n edges. This is basically equal to the time

cost of classical communication for teleportation. Thus the time cost would be halved if we do sequential teleportation or entanglement swapping.

3.1.1 Store-decode-and-Forward Transmission. A delicate step of a repeater-based quantum channel is that the Pauli correction for teleportation can be deferred. For example, If a qubit is sent from node A to B via a router R. Originally, A sends R the measurement outcome m_1 and then R does a Pauli correction according to m_1 . Instead, R can perform a Bell measurement on his qubits and send the outcome m_2 , together with m_1 , to B for Pauli correction. In fact, having $m_1 + m_2$ is enough for B to recover the transmitted qubit. The only quantum operation that R has to do is a Bell measurement. This manner is called store-decode-and-forward transmission, that is, an intermediate node stores the message for Pauli correction from the previous node, updates the message for Pauli correction according to his Bell measurement, and forwards this message to the next node.

Notice that, router R must wait for the message of A about the positions of the qubits to do the Bell measurements since a router may have many qubits. If a Bell measurement is applied to wrong target qubits, quantum information will be destroyed.

3.2 Plain model of Quantum internet

In the plain model of quantum internet, we assume that a full-duplex quantum channel exists between two neighboring quantum devices, such as two hosts, two routers, a host and a router, and they do not pre-share any quantum entanglement. Also these quantum channels are paired with full-duplex classical channels.

When some data are to be sent, they will be segmented and attached with certain header bytes. The resulting packages of information, so-called packets, are then sent through the network to the destination, at which they are reassembled into the original data. Routers that are assigned quantum computing power can take quantum packets as well as classical packets. In particular, any quantum communication between two neighboring quantum devices is accomplished by sending packets of quantum messages over the quantum channel connecting them, together with classical packets over a classical channel connecting them. (For simplicity, the quantum packet and its corresponding classical packet are called a *quantum-classical packet*.) Moreover, we assume that synchronization can be done for the plain model of quantum internet: we assume that a packet of quantum messages and its corresponding packet of classical messages always arrive at the next node simultaneously.

Although the distribution of quantum states over long distances is not possible with current technology, it will be

improved in the near future. Comparing with the repeaterbased model, the plain model is more straightforward, and much more efficient in the following sense. In order to transmit one qubit information to a neighboring router, the previous model requires one-qubit transmission in the entanglement establishment plus two bits classical information transformation.

3.2.1 Store-and-Forward Transmission. A router takes a packet arriving on one of its incoming communication links and forwards that packet on one of its outgoing communication links. In the plain model, a router must receive the entire quantum-classical packet before it can transmit the first qubit and the first bit of the packet onto the outbound link. This is called *store-and-forward transmission*.

4 DIFFICULTIES AND CHALLENGES: QUANTUM PACKET LOSS

As mentioned in the previous section, in classical network, the technique of packet switching is used so that messages are split into small packets, which are then sent independently through the network. Packets from different messages can be interspersed to give greater responsiveness for interactive computing; and individual packets can be re-sent if necessary, rather than entire messages. Whenever one party sends something to the other party, it retains a copy of the data it sent until the recipient has acknowledged that it received it. In a variety of circumstances, the sender automatically retransmits the lost packet using the retained copy.

Within each network, quantum communication may be disrupted due to unrecoverable mutation of the data or missing data. The reasons include quantum decoherence, imperfect operations, the network packet loss, and others.

End-to-end restoration procedures are desirable to allow complete recovery from these conditions in quantum network, we will imitate the packet switching technique and propose the quantum analogue for the quantum internet. In order to ensure that all quantum data are eventually transferred from source to destination, we are facing many difficulties. The no-cloning theorem is a vital ingredient in quantum cryptography, as it forbids eavesdroppers from creating copies of a transmitted quantum cryptographic key. In contrast, it prevents us from using classical techniques in quantum computing. In particular, this affects our problem of transmitting qubits over the internet in two fundamental ways. First, any logical quantum data leak into the environment because the noisy channel cannot be recovered by the communicating parties. Second, the parties hold a joint quantum state that evolves with the protocol, but they cannot make copies of the joint state without corrupting it.

We will employ the techniques of quantum error correcting code together with the classical techniques of packet design to solve the problem of quantum packet loss, see Section 6 for the repeater quantum network, and Section 7 for the plain quantum network.

5 LAYER MODEL

The classical internet has a layered structure, which has conceptual and operational advantages. To introduce a similar structure in the design of quantum internet protocols, quantum network hardwares and softwares are required to operate in the following four layers:

Layered model	Application Layer
	Transport Layer
	Network Layer
	Network Access Layer

The Application Layer creates user quantum data and communicate this data to other applications on another host. The Transport Layer performs host-to-host quantum communications. The Network Layer exchanges quantum datagrams across network boundaries. The Network Access Layer provides the means for the system to deliver quantum data to the other devices on a directly attached network.

In the following, we will take a top-down approach to explain the four layers, first covering the Application Layer and then proceeding downwards, for the quantum repeater network and plain quantum network, respectively.

6 QUANTUM REPEATER NETWORK LAYERS

The quantum repeater network is a teleportation-based network. EPR pairs have to be created between neighboring hosts and routers. Other than that, the data that are actually transmitted in the network are classical bits. Therefore, this model has the following difference from classical network model. To obtain the data to be transmitted, Bell measurements must be jointly applied on the quantum data of the Transport Layer and the particles of the shared EPRs in the Network Access Layer as the initial step of the teleportation. The classical data, measurement outcomes, are packeted in the Transport Layer then passed into the Network Layer.

6.1 Application Layer

The Application Layer is where quantum network applications and their application-layer protocols reside. In a quantum network application, endnodes exchange messages with each other.

In addition to a classical storage, Host i holds two quantum registers A_i and B_i as send buffer and receive buffer, respectively, and also a local working register C_i . At each stage of a

general quantum application protocol, Host i would send A_i to another Host j, receive quantum packet from the network at B_i , and then apply a local operation on its local registers A_i , B_i and C_i . (Note that both the quantum repeater network and plain quantum network can be recast in this framework.)

In the quantum network, the global state of the system can be arbitrary inputs that are allowed, and it is possibly unknown (totally or partially) to hosts.

To send quantum information between two endnodes, messages are divided into smaller packets, which are then sent through communication links and routers. In this scenario, a packet error or loss can destroy the global state, and hence the follow-up tasks. Such a problem will be handled in the next layer–Transport Layer.

6.2 Transport Layer

The Transport Layer of the quantum network transports Application Layer messages between application endpoints. Before providing the two transport protocols, qUDP (Quantum User Datagram Protocol) and qTCP (Quantum Transmission Control Protocol), we first introduce some tools from quantum error detection.

6.2.1 Quantum error detection. The widely used error detection method, including the parity bit, Cyclic Redundancy Check, and the Checksum, can be characterized by a *check* function $f: \{0,1\}^n \mapsto \{0,1\}^k$ in the following encoding procedure: a given n-bit string s is encoded as (s, f(s)) of (n + k) bits. This has been generalized in quantum computing.

Suppose a host wants to send an n-qubit register A through the internet, using a check function f. Let $|\psi\rangle_{A,R}$ be a purified state of A for a reference system R. The encoding is done by firstly appending k ancilla qubits in $|0^k\rangle_S$ to A, and the state of AS is of the form

$$\sum_{0 \le j \le 2^n - 1} \alpha_j |j\rangle_A |\phi_j\rangle_R |0^k\rangle_S.$$

Then, the host applies a controlled unitary U_f on AS to obtain

$$\sum_{0 \le j \le 2^n - 1} \alpha_j |j\rangle_A |\phi_j\rangle_R |f(j)\rangle_S,$$

where U_f is defined by $U_f|j\rangle_A|0^k\rangle_S = |j\rangle|f(j)\rangle$ and is called a *check unitary*. Upon receiving AS, the receiver simply applies the decoding unitary U_f^{-1} to AS. If the data has not been changed, the decoded state would be

$$\sum_{0 \le j \le 2^n - 1} \alpha_j |j\rangle_A |\phi_j\rangle_R |0^k\rangle_S.$$

Then measuring S in the computational basis will give us the outcome 0^k . Otherwise, if the measurement outcome is nonzero, the receiver knows that at least one qubit error has occurred. It could be the case that some error occurs but the measurement outcome is 0^k , which will lead to a decoding

error. This situation occurs with a small chance if the check function is chosen appropriately.

6.2.2 Quantum User Datagram Protocol. Just like its classical counterpart, UDP, the quantum UDP protocol uses a simple connectionless communication model with a minimum of protocol mechanism.

Two communicating quantum processes, says Alice and Bob, use classical UDP sockets to interact. After establishing sockets, Alice, the sender at this round, firstly applies the quantum checksum as the quantum analog of the checksum of the classical UDP protocol using the idea we mentioned in the beginning of this subsection. This is for quantum error detection, and her qubits are now called the quantum segments, says n qubits.

In order to apply for teleportation, Alice has to apply the joint measurements on her segments and the particles of the EPRs. Which EPRs she uses would directly correspond to the next router the segments will send to. Therefore, she asked the Network Layer for proper EPRs by sending the Network Layer the destination, which can be done by the adjusted IP protocol discussed in the next subsection.

After that, she applies the joint measurement on her quantum segments and the particles of EPRs, obtains a 2*n*-bit string *s*. She uses the classical checksum on *s* and sends the resulting classical bits by the classical UDP protocol. Now Alice can generate the qUDP packet for quantum repeater network, using these data in the structure:

where the Indicator is used to indicate that this is qUDP packet of quantum repeater network. Because the action of the routers and receiver is different from the UDP packet of classical internet. Besides the correction of Pauli measurement outcomes, the data part also contains the positions of the corresponding EPRs between two nodes that just been consumed. One can choose the size of this qUDP packet to fit the current UDP structure.

The behavior of the sender is as in Protocol 1. In step 4 the qUDP will split the qubits *D* into several parts, where each part will be teleported to a corresponding router. This is because we want (1) the size of each packet to fit the Maximum Transmission Unit of the Network Layer, and (2) the data been transmitted through different routing paths.

The behaviour of the reciever is as in Protocol 2. Note that the receiver must wait for all pieces of m_1, \ldots, m_t before he can decode the message. The receiver maintains a timeout setting. If some m_i is not received in time, he drops all the received m_j and release the corresponding quantum registers X_j . If there is no packet loss or corrupted during the networks, the state will be successfully transferred to the registers X_1, \ldots, X_t of the receiver.

Protocol 1: Generating qUDP packets

Input: register *A* with *n* qubits

- 1 Append $|0^k\rangle_S$ to A and obtain AS;
- 2 Apply the check unitary U_f to AS and the resulting (n + k)-qubit is now D;
- 3 Ask the Network Layer for collections of EPRs $|\Phi\rangle_{A_1X_1}, \dots, |\Phi\rangle_{A_tX_t};$
 - /* For each j, $|\Phi\rangle_{A_jX_j}$ denotes a collection of EPRs with A_j held by Alice and X_j held by some neighboring router. There should be a total of n+k EPR pairs.
- 4 Divide *D* into *t* groups of qubits $D_1, ..., D_t$, each D_j with size equal to the number of EPRs in A_iX_i .
- 5 Perform Bell measurements on D_j and A_j correspondingly for j = 1, ..., t, and record the measurement outcomes as $s_1, ..., s_t$;
- 6 Construct qUDP packets m_j for data (s_j, j) for $1 \le j \le t$, respectively;
- 7 **return** $m_1, ..., m_k$;
 - /* In the Network Layer m_j will be sent to the router corresponding to X_j .

Protocol 2: Receiver's action of qUDP packet

```
Input: qUDP packets m_1, \ldots, m_t
   /* X_1, \ldots, X_r are the registers of local qubits
       of the corresponding EPRs in m_1, \ldots, m_t. */
 1 Verify the length and checksum of each m_1, \ldots, m_t;
 2 if not valid then
       drop m_1, \ldots, m_t, and release X_1, \ldots, X_t;
 4 else
       Implement the Pauli corrections on X_1, \ldots, X_t
 5
        according to the data in m_1, \ldots, m_t;
       Apply U_f^{-1} on X_1, \ldots, X_t and obtain AS;
       Measure S in the computational basis;
       if Outcome is nonzero then
 8
        release X_1, \ldots, X_t;
10
           Transmission succeed;
11
```

The qUDP provides no recovery procedure for lost packets, and it favors reduced latency over reliability like the classical case. Applications that use qUDP can flexibly define their own mechanisms for handling packet loss.

12 **return** Receiver's action of qUDP packet;

6.2.3 Quantum Transmission Control Protocol. The quantum Transmission Control Protocol (qTCP) introduced here

will provide a connection-oriented, reliable, ordered, and error-checking delivery of a quantum data stream between hosts. In the transmission of application-layer messages, a long message will be divided into shorter segments by qTCP, just like TCP in the classical network. This service includes guaranteed delivery of application-layer messages to the destination and flow control (that is, sender/receiver speed matching).

Quantum information is fragile through the transmission over the internet. To guarantee datagram delivery, a quantum version of information retransmission is needed. However, the no-cloning theorem prevents quantum information from being copied. Herein we show how information retransmission can be achieved using the techniques of quantum secret sharing [11]. This guarantees that the quantum data stream transmitted through qTCP will have exactly the same quantum information and correlation as the original stream.

The qTCP packet is designed as follows:

Classical TCP header	
Indicator	
Pseudo acknowledgement number	
Pseudo Window	
Data	

The indicator implies that this is a qTCP packet for quantum repeater network. Besides the correction of Pauli measurement outcomes, the data part also contains the positions of the corresponding EPRs between two nodes that just been consumed. Others are just the same as classical TCP.

To reach reliable transmission, a packet of quantum information is not transmitted in one step in our qTCP, but in at least two stages. Only if the transmission of both parties is successful, the quantum information is successfully transmitted. The Pseudo acknowledgement number and Pseudo Window are used to record the status of the transmission. We will explain the Pseudo acknowledgement number in the following *Data transfer* part.

The qTCP protocol operations may be divided into three phases. The logical process-to-process connections of qTCP is established by a quantum version of the three-way handshake protocol before entering the data transfer phase. After data transmission is completed, the connection termination closes established virtual circuits and releases all allocated resources.

Connection establishment-quantum three-way handshake.

To establish a connection, we propose a quantum version of the three-way handshake protocol.

Just like its classical counterpart, Host B establishes a passive open, and then Host A initiate an active open. To establish a quantum connection, the quantum three-way handshake protocol operates as follows:

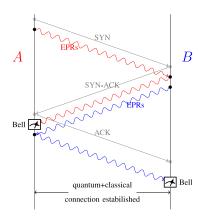


Figure 3: Quantum three-way handshake. The gray lines are classical channels. Two entangled nodes are connected by a wavy line.

- (1) SYN: Host A establishes m local EPR pairs $|\Phi^+\rangle_{A_1A_2}$. Host A sends SYN to Host B, together with the quantum information of A_2 (stored as B_2 by Host B) by a qTCP packet.
- (2) SYN-ACK: Host B receives the qTCP packet. Firstly, he applies the Pauli correction to B_2 , and then sends SYN+1 to Host A, together with the quantum information of B_2 (stored as A_2 by A). Also, Host B establishes m local EPR pairs $|\Phi^+\rangle_{B_3B_4}$. Then Host B sends ACK to Host A, together with the quantum information of B_3 (stored as A_3 by A) by a qTCP packet. After verifying SYN+1, Host A performs a multi-qubit Bell measurement on A_1A_2 and checks whether the measurement outcome is 0^{2m} .
- (3) ACK: Host A sends ACK+1, and transfers the quantum information of A_3 to B_3 of Host B. After verifying ACK+1, Host B performs a multi-qubit Bell measurement on B_3B_4 and check whether the measurement outcome is 0^{2m} .

At this point, both Hosts have received an acknowledgment of the connection. One can observe that the quantum channel between two hosts is noiseless if and only if the distribution of EPRs is noiseless. To see the efficiency of detecting the channel noise, we consider the extreme case that the entanglement is destroyed either during the teleportation from A_2 to B_2 or from B_2 to A_2 . Assume the state of A_1A_2 at the end of step 2, $\rho_{A_1A_2}$, is not entangled (or so-called *separable*). In other words, there exist probability distribution p_i and quantum states $|\psi_i\rangle_{A_{1,i}}$ and $|\varphi_i\rangle_{A_{2,i}}$ such that $\rho_{A_1A_2} = \sum_i p_i |\psi\rangle\langle\psi|_{A_{1,i}} \otimes |\varphi\rangle\langle\varphi|_{A_{2,i}}$. When we perform a

multi-qubit Bell measurement on it, the probability of obtaining 0^{2m} satisfies

$$\begin{split} &\operatorname{tr}(\left\langle \Phi^{+\otimes m} \middle| \rho \middle| \Phi^{+\otimes m} \right\rangle) \\ &\leq & \max_{i} \operatorname{tr}(\left\langle \Phi^{+\otimes m} \middle| |\psi_{i} \middle| \psi_{i} \middle| \otimes |\varphi_{i} \middle| \left\langle \varphi_{i} \middle| |\Phi^{+\otimes m} \middle| \right\rangle) \\ &= & \max_{i} |\left\langle \Phi^{+\otimes m} \middle| \psi_{i} \otimes \varphi_{i} \middle| \right|^{2} \\ &\leq & \frac{1}{2^{m}}. \end{split}$$

The steps 1, 2 establish the classical and quantum connections for one direction and it is acknowledged. The steps 2, 3 establish the quantum connection for the other direction and it is acknowledged. With these, a full-duplex quantum communication is established.

Data transfer

A reason that the classical TCP works well is because classical information can be correctly read and copied. When one party sends something to the other, it will keep a copy until it gets acknowledged by the recipient. In a variety of circumstances, a sender may automatically retransmit the data using the retained copy.

To handle quantum retransmission, we start with a simple question:

How to achieve reliable transmission of a one-qubit state $|\psi\rangle$ from Host A to Host B through a noisy quantum channel?

We consider a multi-round protocol, which can always be modelled as follows:

- (1) Host A encodes $|\psi\rangle$ into $|\varphi\rangle_{A_1A_2A_3}$, and sends register A_2 to Host B.
- (2) Host B sends Host A the acknowledgement whether the transmission is successful.
 - (a) If unsuccessful, the hosts will do other actions.
 - (b) Otherwise, Host A sends A_3 to Host B.

The reliability requires at least the following fact: once a transmission failed, the hosts are able to recover the original state from the remaining qubits.

Suppose the first step of transmitting A_2 to Host B fails, the left A_1A_3 system is enough to recover the original state $|\psi\rangle$. Then the information of A_2 is not enough to recover $|\psi\rangle$. Otherwise, this provides a cloning procedure, contradicts to the no-cloning theorem. This implies that A_2 alone contains no information of the original state $|\psi\rangle$. In the stage of (2b), to make sure that the information of the original state is not lost even when A_3 is lost, A_1A_2 must contain enough information to recover the original state $|\psi\rangle$. Moreover, we want that if the transmission of A_3 successes, Host B can recover the original state $|\psi\rangle$ from A_2A_3 .

In other words, we want an encoding scheme from $|\psi\rangle$ to $|\varphi\rangle_{A_1A_2A_3}$ such that any two of $\{A_1,A_2,A_3\}$ can reconstruct the unknown $|\psi\rangle$. This can actually be done by the

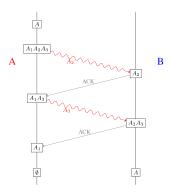


Figure 4: Successful quantum transmission.

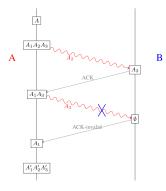


Figure 5: UnsuccessfulQuantum transmission in the second send. Host A has to do one more recursion.

(2, 3)-threshold scheme of quantum secret sharing [11], using the theory of quantum error-correcting codes. An (k, n)threshold scheme is such that any k shares, but not fewer, 1 can jointly recover the secret.

Now we outline our quantum retransmission procedure. First Host A sends A_2 to Host B after generating $A_1A_2A_3$ from A. If A_2 is not received, then Host A reconstructs A_1 from A_1A_3 , and runs the procedure again. Otherwise if A_2 is received, then Host A sends A_3 to Host B. If it is received, Host B can reconstruct A from A_2A_3 . If A_3 is not received, Host A repeats the procedure on the remaing A_1 . The procedure can be repeated recursively until Host B has enough information to recover A or the procedure aborts after a number of rounds. More explicitly, the transmission succeeds if two consecutive messages are correctly received by Host B.

In a less noisy channel, one can make sure that this scheme always succeeds within finite steps. However, a potential problem here is that the storage of Host B for this single message is not unbounded. Although Host B may need an unbounded classical data structure to maintain the status of the transmission, he has only four types of possible status:

• B is waiting for some $A_2^{(i)}$ since the previous $A_2^{(i-1)}$ is not received or valid;

```
Input: A: register with qubits to be sent
1 Enocde A by the (2, 3) threshold scheme and obtain
   A_1A_2A_3;
_2 k \leftarrow \text{true};
3 while k do
     Send A_2 to Host B;
      /* Host B will send valid acknowledgement
         to Host A if he received B
          successfully.
                                                        */
      if Valid acknowledged then
5
```

Protocol 3: Quantum retransmission(A)

```
Send A_3 to Host B;
6
          if Valid acknowledged then
7
               Release A_1;
8
               k \leftarrow \text{false}:
               /* Host B is able to recover A by
                   decoding A_2A_3.
           else
10
               Call Quantum retransmission(A_1);
11
```

/* If data packet is not arrived within expected time or data is damaged. Host B sends invalid acknowledgment.

else 12 Regenerate the original A from current A_1A_3 ; 13 Call Quantum retransmission(*A*); 14

A₂⁽ⁱ⁾ is received, and B is waiting for A₃⁽ⁱ⁾;
 A₂⁽ⁱ⁾ is received, but the corresponding A₃⁽ⁱ⁾ is not valid;
 A₂ and A₃ are both validly received.

The Pseudo acknowledgement number and Pseudo Window of the qTCP packet are used for the acknowledgement of the status of Host B.

Now we give the construction of our qTCP packet as follows. For any register A with n qubits, Host A first applies a check unitary U_f to A and ends with n+k qubits as previously discussed in the qUDP part.

- (1) Use the (2,3) threshold scheme to obtain 3(n+k) qubits $A_1A_2A_3$.
- (2) Ask the Network Layer for EPRs, perform Bell measurements, and record the outcome s.
- (3) Construct a classical TCP packet for s and send it.

By carefully choosing n and k, we can ensure that s can be put in one TCP packet.

The sender just combines this with the Quantum retransmission Protocol 3.

The router's action for any packet is illustrated in Protocol 4 in qUDP.

Host B's actions for any packet are

- (1) Verify classical checksum;
- (2) Apply Pauli correction;
- (3) Store it.

Once all the pieces are received, Host B

- (1) Decodes the (2, 3)-threshold scheme;
- (2) Performs U_f^{-1} and Bell measurements to verify the quantum checksum;
- (3) Acknowledges Host A;
- (4) Uses the *n* qubits and releases the buffer.

It would not be surprising that most techniques in classical TCP, including Doubling the Timeout Interval, Fast Retransmit, selective acknowledgment, for congestion control are applicable to this quantum repeater network by using this qTCP data structure.

Let A be a register that is about to be sent. Host A maintains statuses of his data for some A_2 and A_3 , "Sent and Acknowledged"; "Send But Not Yet Acknowledged", "Not Sent, Recipient Ready to Receive"; "Not Sent, Recipient Not Ready to Receive". Host A always holds some corresponding A_1 . Similarly, Host B maintains a classification of his data for some A_2 and A_3 , "Received and ACK Not Send to Process", "Received Not ACK", "Not Received".

The "Pseudo acknowledgement number" and "Pseudo Window" are used to record these statuses. Together with "Acknowledgement number" and window, sliding window protocol can be implemented.

Connection termination

To terminate the connection, we just use the four-way handshake as in classical TCP, where each side of the connection is terminated and each buffer is released independently.

6.3 Network Layer

After receiving a transport-layer segment and a destination address from the Transport Layer protocol (qUDP or qTCP) in a source host, the Network Layer then provides the service of delivering the segment to the Transport Layer in the destination host.

We just use the celebrated Internet Protocol (IP). The routing protocol can be slightly modified such that quantum packets must be transmitted to a router with quantum power. This can be done by the associate one-bit index of the IP. In particular, each host and router maintains a dynamic table with the information about the numbers of the EPRs that he shares with his neighbor. The neighbor shared more EPRs has priority in the routing protocol.

Now we describe the action of the router for qUDP packet or qTCP packet as follows. The behaviour of the router is very different from the behaviour of router in classical networks. The data of quantum repeater network are just the Pauli measurement outcomes. It can only be used in completing

```
Protocol 4: Router's action
```

Input: m: qUDP packet or qTCP packet
/* X is the register of the corresponding
 EPRs. */

- 1 Verify the length and checksum of *m*;
- 2 if not valid then
- drop m and release X;

4 else

5

- Ask the Network Layer for EPRs $|\Phi\rangle_{YZ}$;
 - /* $|\Phi\rangle_{YZ}$ is a collection of EPRs with local Y and Z being held by the next neighboring router or destination.
- Apply Bell measurements to *X* and *Y* correspondingly and record the measurement outcomes *s*;
- 7 Construct new packets \tilde{m} based on s and m;
- 8 Send the new packets \tilde{m} to the node holding Z;
- 9 return Router's action;

the teleportation, which would accomplish the transformation of quantum states. The classical checksum is used to check the data integrity. In order to transmit the "received" quantum state to the next node, the router has to implement teleportation, which would generate new data. This data has no correlation with the received classical data, generally. The router then replaces the data and checksum by the newly generated data in the qUDP packet or qTCP packet to obtain a new one.

6.4 Network Access Layer

The Network Access Layer in the quantum repeater network provides the services that a classical Network Access Layer does, including the CRC checking for the classical data of qTCP. It provides the distribution of entanglement, in particular EPRs, as an additional service. The entanglement distribution is the lifeline of the quantum repeater network since it determines the connectivity of the quantum network due to the irreplaceable role of EPRs in quantum teleportation.

Many entanglement distribution protocols can be used to establish EPRs between node and quantum repeaters. Here, we use the idea of quantum Gilbert-Varshamov bound [19] for low noise quantum channel. We have the following robust entanglement distribution protocol, where $H(\cdot)$ is the binary entropy function and ϵ is a noise parameter. After obtaining these short-range EPRs, teleportation is used to establish the EPRs between neighbor nodes. Hosts and routers would need to record their positions of the EPRs and the destinations that the EPRs connected.

Protocol 5: Robust Entanglement Distribution

```
Input: n: the desired number of EPRs

1 C \leftarrow Error-Correcting Code with rate 1 - \Theta(H(\epsilon))
guaranteed by the quantum Gilbert-Varshamov bound;

2 if Alice then

3 | Prepare n(1 + \Theta(H(\epsilon))) EPRs, |\Phi\rangle_{AB'};

4 | Transmit C(B') to Bob;

5 else if Bob then

6 | Receive C'(B');

7 | B \leftarrow Decoding of C'(B');

8 |\Phi\rangle_{AB} denotes the shared n EPRs;

9 return Robust Entanglement Distribution;
```

The entanglement is a perishable resource in the sense that the entanglement among entangled parties is progressively lost over time. Nodes of the internet need to refresh their EPRs constantly. To do so, the time that the EPRs are created is also needed to be recorded.

It would be convenient if each node in the network is quantum connected to all his neighbors, each with a considerable number of EPRs enough for transmitting a UDP packet or qTCP packet, in its free time. This is just in case of potential request quantum communication to some neighbor.

When a node is working on qUDP or qTCP transformations, he would need to dynamically change its quantum connections by updating the information of EPRs.

7 PLAIN QUANTUM NETWORK LAYERS

In this section, we outline the quantum network protocols for the plain quantum Network Layers. In this model, the communication links between hosts and routers are quantum channels. The transmitted information flow through the network is quantum.

As the progress of quantum information transformation technology, the quantum state distribution will be more and more accurate between neighboring nodes of the network. This would be more suitable for modeling such quantum network. This model is more clear as its quantum communication links are fixed. Comparing with quantum repeater network, the behaviour of the layers in this model is closer to that of the classical internet layers.

The Application Layer is the same as that of the quantum repeater network as discussed in Subsubsection 6.1.

7.1 Transport Layer

The qUDP and qTCP for plain quantum network is different from those of quantum repeater network in the following sense.

In this model, the data packet is a classical packet head along with several qubits as quantum packet. As the two components of a quantum packet, they always arrive at the next node simultaneously. The classical packet head of qUDP (qTCP) is exactly the same as that of UDP (TCP), where the length is given by the number of qubits. The data part contains the qubits.

- (1) The quantum information transformation is done by direct transfer via a qUDP or qTCP packet rather than transmitting classical Pauli correction bits together with EPRs, including the three-way quantum handshake. Therefore this qUDP or qTCP header has no information about the data.
- (2) In the quantum repeater network, there are one round quantum checksum and one round of classical checksum. The classical checksum is verified by router and renewed. The quantum checksum would only be verified by the receiver. In the plain quantum network, there are two rounds

quantum checksum, which would be only checked by the receiver, not the router.

7.2 Network Layer

The Network Layer is simpler than the quantum repeater network case. Internet Protocol (IP) can be employed for addressing host interfaces based on the classical head information of the qUDP or qTCP packet. As we mentioned at the end of Section 3, the routers in this model use store-and-forward transmission, but not checking for the validity of data packet.

7.3 Network Access Laver

The Network Access Layer of plain quantum network provides the services of quantum CRC checking, as we introduced in the quantum error detection of Section 6.

8 CONCLUSIONS AND FUTUREWORK

We have discussed the interconnection of packet quantum network intercommunication for quantum repeater network and plain quantum network. In particular, we have described quantum User Datagram Protocols which allow connectionless communication model with a minimum of protocol mechanism and quantum Transmission Control Protocols which provide reliable quantum packet communication, respectively.

The next important step is to studying techniques for congestion avoidance and control of quantum network protocols. In classical network, packet switching introduces new complexities, since the packets must be re-ordered and reassembled at the destination. Also, since there are no dedicated

circuits, the network links can become congested, potentially resulting in lost packets. Quantum effects bring new challenges in developing congestion control algorithms for qTCP.

Another interesting project is to produce a detailed specification of these protocols and implement a prototype so that some initial simulation, and in the future some experiments, with it can be performed.

9 ACKNOWLEDGEMENT

This work does not raise any ethical issues.

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