# Quantum Communication for Wireless Wide-Area Networks

Sheng-Tzong Cheng, Chun-Yen Wang, and Ming-Hon Tao

***Abstract*—In this paper, a quantum routing mechanism is proposed to teleport a quantum state from one quantum device to another wirelessly even though these two devices do not share EPR pairs mutually. This results in the proposed quantum routing mechanism that can be used to construct the quantum wireless networks. In terms of time complexity, the proposed mechanism transports a quantum bit in time almost the same as the quantum teleportation does regardless of the number of hops between the source and destination. From this point of view, the quantum routing mechanism is close to optimal in data transmission time. In addition, in order to realize the wireless communication in the quantum domain, a hierarchical network architecture and its corresponding communication protocol are developed. Based on these network components, a scalable quantum wireless communication can be achieved.**

***Index Terms*—EPR pair, handover, quantum bit (qubit), quantum entanglement, quantum routing, quantum teleportation, wireless wide-area network (WAN).**

## I. Introduction

QUANTUM computation and quantum information processing [9], [19] is an emerging area whose study combines the exploration of quantum mechanics and new physical principals to solve the hard problems in classical computation. In literature, outstanding algorithms such as *Shor's factoring algorithm* [22] and *Grover's database search algorithm* [4], [13], [16] have been developed. It shows that quantum-based computers are more powerful than traditional Turing machines. Due to its potential impact and significance, quantum information science has drawn more and more attentions in the decade.

One of the most important applications in quantum information science is the quantum teleportation [23]. Quantum teleportation employs a particular quantum property called *quantum entanglement*, which allows quantum devices to transport a specific quantum state to another site at a distance by transmitting classical bits rather than quantum bits. To achieve quantum teleportation, shared entanglement is needed. Shared entanglement can be accomplished by generating an EPR (named after Einstein, Podolsky, and Rosen) pair and distributing the pair to the source and destination through *quantum wires* [1].

However, there are lots of challenges in exploiting the quantum teleportation in the area of wireless communication [5], [10]. One of the main challenges is that the EPR pairs generated at the *EPR generator* cannot be distributed to wireless quantum device through the air. As a result, wireless quantum devices cannot set up EPR pairs instantaneously. Even if quantum devices can set up EPR pairs by "plugging" in the quantum wires while they are static, it is still unreasonable for a limited storage mobile device to keep many EPR pairs entangled with all possible communication parties for the future use in wireless environment. Therefore, it motivates the need to establish a new quantum mechanism, which allows the teleportation of a quantum state from one site to a remote site even when the two sites do not share EPR pairs mutually.

This paper represents the first attempt to address the issue of wireless communication in the quantum domain. A quantum routing mechanism is proposed to construct the quantum wireless communication networks. By executing the quantum circuits at the intermediate nodes in parallelism, the data transmission time by performing the quantum routing mechanism is almost the same as that by applying quantum teleportation, regardless of the number of intermediate nodes in between the source and the destination. This enables a quantum device to teleport a quantum state to another device that does not share EPR pairs mutually, at the time complexity nearly identical to that case in which EPR pairs are shared.

In addition, in order to realize the quantum routing mechanism, a hierarchical network architecture is developed. Based on the network architecture, a new wireless communication protocol is also presented. This paper also addresses several *radio resource management* (RRM) issues that shall be investigated so as to implement the quantum wireless communication architecture.

The rest of this paper is organized as follows. In Section II, the general concepts about quantum computation and quantum teleportation are introduced. Related research is surveyed as well. In Section III, the proposed quantum routing mechanism is depicted. In Section IV, a hierarchical network architecture is proposed for wireless *wide-area network* (WAN) to realize the quantum wireless communication. The corresponding wireless communication protocol is also presented. Section V lists out some open problems and discusses the possible solutions to these problems. Finally, conclusion remarks are drawn in Section VI.

## II. Notations and Preliminaries

In this section, we briefly introduce definitions and terminologies used in describing the proposed mechanism throughout this paper. In-depth treatments of the notations can be found in literature [12].

Manuscript received March 30, 2004.
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Digital Object Identifier 10.1109/JSAC.2005.851157

### A. Quantum States

The *bit* is the fundamental unit in classical digital systems to express data and store information. Analogous to classical bits, the underlying unit in quantum information science is a *quantum bit (qubit)*. Two possible states for a qubit are denoted by the states $|0\rangle$ and $|1\rangle$. These states can be regarded as the states 0 and 1 for a classical bit. However, unlike a classical bit that must be in a state either 0 or 1, a qubit can be in both state $|0\rangle$ and state $|1\rangle$ at the same time. In general, a qubit state can be represented as a linear combination of these two states. A qubit $|\phi\rangle$ can be symbolized in the form of

$$|\phi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

where $\alpha$ and $\beta$ are complex numbers.

This special phenomenon in quantum computing is called *superposition*. Note that it is impossible for us to determine whether a qubit is in state $|0\rangle$ or $|1\rangle$ by examining the values of $\alpha$ and $\beta$. However, when we *measure* a qubit in superposition state, the entire qubit system would collapse into one of its basis (e.g., either $|0\rangle$ or $|1\rangle$). As for which state we would obtain, it is determined by the absolute square of its coefficient. In other words, we get the qubit in state $|0\rangle$ with probability $||\alpha||^2$, or in state $|1\rangle$ with probability $||\beta||^2$. Thus, $\alpha$ and $\beta$ are often called *probability amplitudes*. In addition, since the sum of probabilities must equal 1 to satisfy the axiom of probability, we get the equation that $||\alpha||^2 + ||\beta||^2 = 1$.

Furthermore, two or more qubit systems can be built up by composing multiple independent qubits. Take a two classical bit system as an example; there would be four possible states, 00, 01, 10, and 11. Accordingly, a two-qubit system also has four possible states. And they can be expressed by $|00\rangle, |01\rangle, |10\rangle$, and $|11\rangle$. Similarly, a two-qubit system can be represented as a linear combination of these four states in the following form:

$$|\phi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \tag{2}$$

where the probability amplitudes $\alpha, \beta, \gamma$, and $\delta$ are all complex numbers such that $||\alpha||^2+||\beta||^2+||\gamma||^2+||\delta||^2 = 1$. Moreover, in order to compose two or more single qubit systems together, the *tensor product* operator $\otimes$ is adopted. For example, a two-qubit system composed of two single qubit systems $|\phi\rangle = a|0\rangle + b|1\rangle$ and $|\psi\rangle = c|0\rangle + d|1\rangle$ can be represented as $|\phi\rangle \otimes |\psi\rangle = |\phi\psi\rangle = ac|00\rangle + ad|01\rangle + bc|10\rangle + bd|11\rangle$.

### B. Quantum Unitary Gates

In digital information processing, combining with some fundamental logic operators so as to compete a specific task is called a logic gate. Such as the classical *NOT* gate, *AND* gate, *OR* gate, *XOR* gate, and so on. Analogously, in quantum computing, a set of operators that can manipulate a quantum system to accomplish a specific computation is called a *quantum gate*. In this section, we start out to describe some quantum gates for subsequent sections.

Fig. 1 illustrates three important single qubit gates. Similar to the classical *NOT* gate, the quantum $X$ gate applied on a single qubit can be used to flip its state $|0\rangle$ and $|1\rangle$. Therefore, as shown in Fig. 1, when we send a qubit $|\phi\rangle = \alpha|0\rangle + \beta|1\rangle$ through the quantum $X$ gate, then the corresponding output is $|\phi'\rangle = \beta|0\rangle + \alpha|1\rangle$. The $Z$ gate is used to flip the phase of the state $|1\rangle$. In other words, it can exchange $\alpha|0\rangle + \beta|1\rangle$ and $\alpha|0\rangle - \beta|1\rangle$. The final *Hadamard* $H$ gate is one of the most useful quantum gates. The $H$ gate can turn $|0\rangle$ into $(1/\sqrt{2})(|0\rangle + |1\rangle)$ and turn $|1\rangle$ into $(1/\sqrt{2})(|0\rangle - |1\rangle)$. It can also be treated as a *Fourier transformation* (FT) with radix-2 [21].

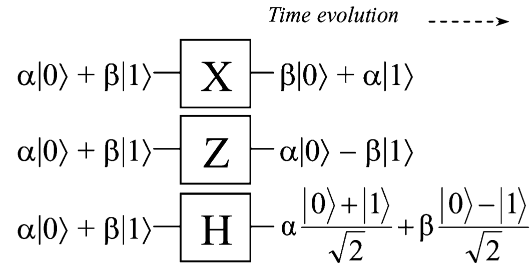


Fig. 1. Quantum single qubit gates.

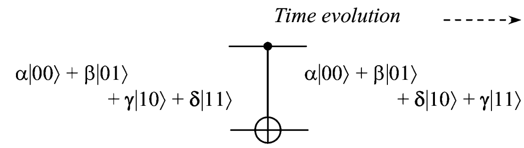


Fig. 2. Quantum *controlled-NOT* gate applied on two-qubit system.

Fig. 2 illustrates the circuit of the *controlled-NOT* (CNOT) gate for processing two qubits. It has been shown that all multiple qubit gates can be composed from the CNOT gates and single qubit gates [18], [20]. As shown in Fig. 2, the CNOT gate has two inputs. One is the control qubit and the other is the target qubit. When the control qubit is in state $|0\rangle$, it does nothing. On the other hand, the control qubit is in state $|1\rangle$, then it would flip the target qubit's state. In other words, the CNOT gate is used to exchange $|10\rangle$ and $|11\rangle$.

### C. Quantum Teleportation

Quantum teleportation [23] is a technique used to teleport a quantum state from a source node to a faraway destination node. Quantum teleportation is achieved by applying the property of EPR pairs. An EPR pair can be seen as a bridge between quantum devices, and quantum teleportation can be regarded as transporting a specific qubit by passing it through the bridge. An EPR pair is a two-qubit system in maximally entangled state and can be denoted by $(1/\sqrt{2})(|00\rangle + |11\rangle)$. In the beginning, an EPR pair is shared between source and destination, with the source (e.g., *Alice*) keeps one qubit and the destination (e.g., *Bob*) holds the other qubit, then, with the aid of the EPR pair, *Alice* can communicate qubit information with *Bob* at a distance by only performing local operations and classical communication. So EPR pairs are called entanglement-assisted quantum channels in some literatures [8].

Fig. 3 shows the quantum circuit of quantum teleportation. Note that single lines in Fig. 3 represent quantum data while the double lines stand for classical information. Furthermore, it can be seen from Fig. 3 that *Alice's* second qubit and *Bob's* qubit form an EPR pair in the beginning. When *Alice* wants to deliver a qubit $|y\rangle$ to *Bob*, she sends her two qubits through a *CNOT* gate. After that, she performs a *Hadamard* gate on the first qubit. Afterwards, she measures the qubits and transmits

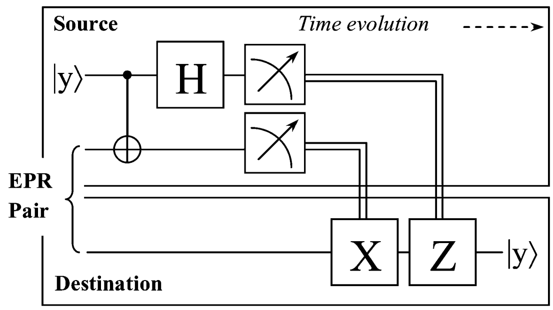


Fig. 3. Quantum circuit for quantum teleportation.

the measurement outcomes to *Bob* through the classical channel. Once *Bob* receives the two classical bits, he knows that *Alice* has teleported a qubit state to him. Based on the received two classical bits, the quantum state $|y\rangle$ can be reconstructed by the appropriate operations.

We observe that quantum teleportation can be further improved. It is because quantum teleportation assumes that source and destination share a lot of EPR pairs in advance. But it is impossible and unreasonable for a limited storage quantum mobile device to share EPR pairs with all the other quantum devices. Consequently, in this paper, we investigate this problem and propose a practical mechanism to achieve quantum teleportation even if the source and destination do not share any EPR pair mutually.

### *D. Related Work*

This paper represents the first attempt to investigate the issue about wireless communication for quantum mobile devices. Here, we survey the related literatures of quantum communication in wired networks. Oskin *et al.* [1] defined a quantum wire to move quantum data from one spatial location to another. Moreover, it was also pointed out that for a long distance data transmission, it is more faithful by using quantum teleportation than directly transmitting through quantum wires.

Besides that, in order to avoid a fully meshed quantum wires in the networks, Tsai and Kuo proposed a nonblocking digital switching architecture in the quantum domain [3]. Moreover, the quantum switch can support unicasting with time complexity of O(1), as well as multicasting with time complexity of $O(\log n)$.

Furthermore, for quantum teleportation to work perfectly, pure EPR pairs are required. It is important to design a method to extract pure EPR pairs from polluted ones. Therefore, an entanglement purification protocol [15] was proposed. It was done by sacrificing some of the entangled pairs to increase the purity of remaining ones. On the other hand, Barnum *et al.* [2] proposed another purity testing protocol, which only checks whether EPR pairs are correct or not, but does not repair wrong ones. Moreover, Ambainis *et al.* [7] presented a more general entanglement purification protocol and proved that there really exist some methods that output states arbitrarily closed to pure EPR pairs with very high successful probability.

In addition, Nayak *et al.* [8] discussed the problem of *dense quantum coding* and derived optimal bounds on the number of quantum bits required to transmit multiple classical bits over an entanglement-assisted quantum channel for a given tolerable erroneous probability. Ambainis *et al.* [6] exhibited a quantum encoding method to encode two classical bits into one qubit with successful probability 0.85. Furthermore, they also presented a quantum encoding mechanism to encode three classical bits into one qubit with successful probability 0.78.

Sharing entanglement before transmission is an important stage to achieve quantum communication. However, in a wireless environment, EPR pairs cannot be transmitted to the sender or receiver via quantum wires. Consequently, EPR pairs cannot be set up between them. Therefore, if a quantum device would like to communicate with another quantum mobile device wirelessly, a new mechanism is needed. In this paper, we develop a quantum routing mechanism for quantum mobile devices to achieve wireless communication.

## III. Quantum Routing Mechanism

Two important schemes in the proposed quantum routing mechanism are quantum relay and EPR-pair bridging. The principle of quantum relay is to perform the quantum teleportation hop by hop from the source to destination when there is (are) intermediate node(s) in between. The significance of EPR-pair bridging is to speed up the whole quantum relay process by performing the quantum teleportation at each intermediate node in parallelism. In the following two sections, the principles and circuits for quantum relay and EPR-pair bridging will be given.

### *A. Quantum Relay Scheme*

Quantum teleportation is known to be the most efficient mechanism to accomplish qubit transmission in wired line. To perform quantum teleportation, it is necessary for source and destination to share entangled qubits like EPR pairs in advance. However, in a networking environment, it is impossible for one device to share EPR pairs with all possible communication parties simultaneously. Even if there exist EPR generators and quantum wires for wired quantum nodes to establish entangled EPR pairs, it is still infeasible to transmit EPR pairs to mobile devices wirelessly.

Quantum relay solves the above problem by performing quantum teleportation hop by hop across the network. Consider the following example in which a qubit information is to be sent from source (e.g., *Alice*) to destination (e.g., *Bob*). As shown in Fig. 4, *Alice* and *Bob* do not share EPR pairs mutually, namely, no active quantum channel exists between them. However, if there exists an intermediate node (e.g., *Candy*) that shares EPR pairs with both source and destination, then the quantum teleportation can still be performed by delivering the qubit information from *Alice* through *Candy* to *Bob*. As shown in Fig. 4, *Candy* shares EPR pairs with *Alice* and *Bob*, respectively, at the first stage. Then, the quantum state $|y\rangle$ is delivered from *Alice* to *Candy* at the second stage. Finally, after *Candy* receives $|y\rangle$, she forward it to *Bob*. The corresponding quantum circuit for the quantum relay scheme is illustrated in Fig. 5.

By exploiting the quantum relay scheme, quantum wireless communication can be carried out even if the source and destination don't share any EPR pairs mutually. Nevertheless, since

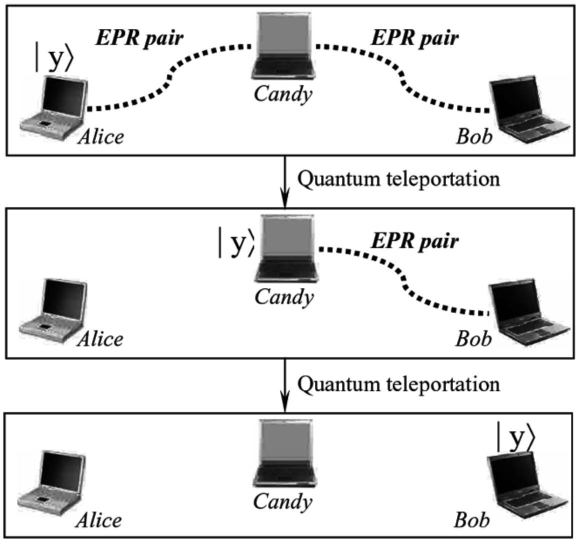


Fig. 4. Skeleton diagram for quantum relay scheme.

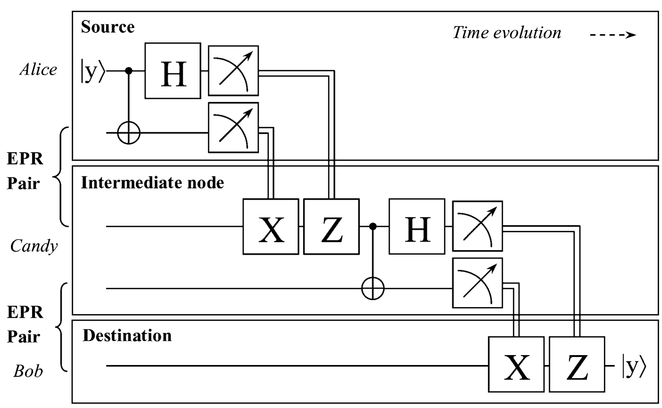


Fig. 5. Quantum circuit for quantum relay scheme.

the target qubit is transmitted through each intermediate node, this scheme is lack of security and privacy, Moreover, the data transmission time it requires is in proportion to the number of the routing hops. To overcome the above drawbacks, we propose the scheme of the EPR-pair bridging.

## *B. EPR-Pair Bridging*

In the quantum relay scheme, each intermediate node shares EPR pairs with its upstream node and downstream node. We observe that each intermediate node can be served as the role of the EPR generator and the node is able to establish the entanglement-assisted quantum channel between its upstream and downstream nodes. The observation motivates the development of EPR-pair bridging. The accuracy of the EPR-pair bridging can be verified as follows.

The schematic quantum circuit for an intermediate node to establish an EPR pair between source and destination is illustrated in Fig. 6. We denote the EPR pair shared by source (i.e., *Alice*) and the intermediate node (i.e., *Candy*) as $(1/\sqrt{2})(|0\rangle_A|0\rangle_C + |1\rangle_A|1\rangle_C)$. Similarly, the EPR pair shared by intermediate node and destination (i.e., *Bob*) can be

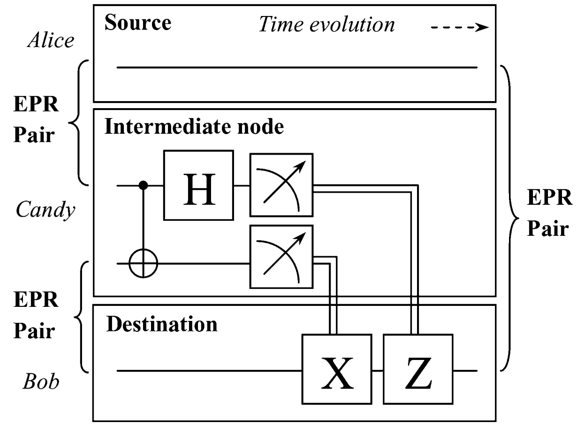


Fig. 6. Quantum circuit for an intermediate node to establish an EPR pair between source and destination.

represented by $(1/\sqrt{2})(|0\rangle_C|0\rangle_B + |1\rangle_C|1\rangle_B)$, then the entire four-qubit system can be represented as

$$\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_C + |1\rangle_A|1\rangle_C) \otimes \frac{1}{\sqrt{2}}(|0\rangle_C|0\rangle_B + |1\rangle_C|1\rangle_B). \quad (3)$$

After applying the *CNOT* gate, we obtain

$$\frac{1}{2}[|0\rangle_A|0\rangle_C(|0\rangle_C|0\rangle_B + |1\rangle_C|1\rangle_B) + |1\rangle_A|1\rangle_C(|1\rangle_C|0\rangle_B + |0\rangle_C|1\rangle_B)]. \quad (4)$$

Next, performing the *Hadamard* gate, we obtain

$$\frac{1}{2\sqrt{2}}[|0\rangle_A(|0\rangle_C + |1\rangle_C)(|0\rangle_C|0\rangle_B + |1\rangle_C|1\rangle_B) + |1\rangle_A(|0\rangle_C - |1\rangle_C)(|1\rangle_C|0\rangle_B + |0\rangle_C|1\rangle_B)]. \quad (5)$$

Expression (5) can be rewritten as

$$\begin{aligned}\frac{1}{2\sqrt{2}}[&|00\rangle_C(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B)\\ &+ |01\rangle_C(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)\\ &+ |10\rangle_C(|0\rangle_A|0\rangle_B - |1\rangle_A|1\rangle_B)\\ &+ |11\rangle_C(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)]. \quad (6)\end{aligned}$$

From expression (6), it can be seen that the entire system consists of four parts depending on the states of the two qubits that *Candy* holds. Therefore, as long as the intermediate node measures its own two qubits, it would set up four terms of entangled qubits between source and destination. For example, if *Candy's* measurement outcome is in the state $|00\rangle$, then the entangled qubits must be in the state $(1/\sqrt{2})(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B)$ that is exactly what the intermediate node desires to set up. On the other hand, if *Candy's* measurement outcome is $|01\rangle$, then the entangled qubits are in the state $(1/\sqrt{2})(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)$. Depending on the measurement outcome in the intermediate node, the destination would have the information about the entangled qubits' state. So it can fix up the entangled qubits to EPR pairs via either applying nothing, $X$ gate, $Z$ gate, or both

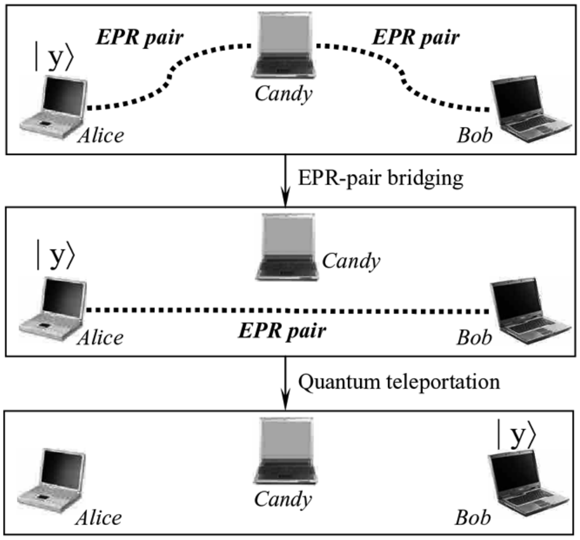


Fig. 7. Skeleton diagram for using the EPR-pair bridging.

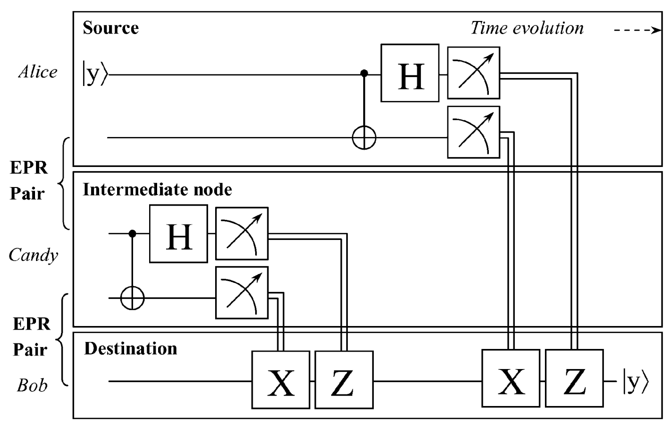


Fig. 8. Quantum circuit for teleporting a qubit by using EPR-pair bridging.

$X$ and $Z$ gates, then the EPR pair between source and destination would be built.

The quantum circuit for establishing EPR pairs in Fig. 6 is the extension of the quantum teleportation circuit. It is illustrated that the quantum teleportation is able to teleport a qubit to a remote quantum device even if the qubit is entangled with other qubits. For this reason, the EPR-pair bridging can also be regarded as teleporting the qubit, which is entangled with the qubit at *Alice's* side, from intermediate node to destination.

After the intermediate node sets up an EPR pair between source and destination, then source is able to perform the quantum teleportation so as to transport the quantum state $|\mathrm{y}\rangle$ to destination. Thus, the EPR-pair bridging diagram for delivering a qubit from source to destination can be illustrated in Fig. 7. At first, the intermediate node is responsible for establishing EPR pair between source and destination. Then, with the aid of the entanglement-assisted quantum channel, source would be able to trigger the quantum teleportation so as to accomplish qubit transmission. The entire quantum circuit for EPR-pair bridging is sketched in Fig. 8.

It can be shown that the time complexity of this EPR-pair bridging is independent of the number of intermediate nodes. We will show later that this is because all the intermediate nodes

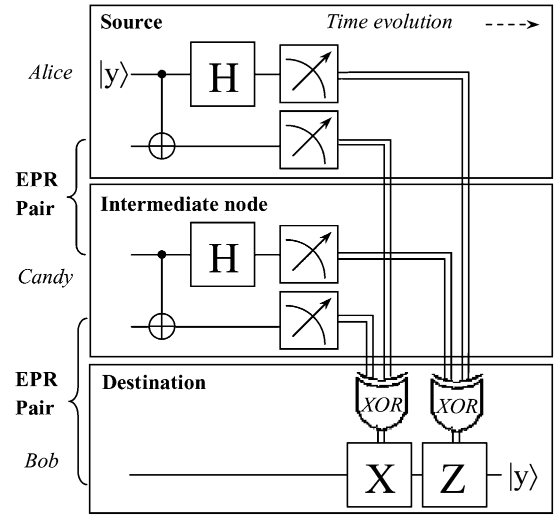


Fig. 9. Quantum circuit for quantum routing mechanism.

can perform the EPR-pair bridging in parallelism at the same time.

## C. Quantum Routing Mechanism

Quantum routing mechanism combines the concepts of the quantum relay scheme and the EPR-pair bridging. The circuit for quantum routing mechanism is shown in Fig. 9. Note that there is no entangled qubits between source and destination. Instead, there exists an intermediate node, which shares EPR pairs with both source and destination.

First of all, suppose that the quantum state to be teleported is $|\mathrm{y}\rangle = \alpha|0\rangle + \beta|1\rangle$, where $\alpha$ and $\beta$ are probability amplitudes. As shown in Fig. 9, source's second qubit and intermediate node's first qubit construct an EPR pair and so do the intermediate node's second qubit and destination's qubit. In the beginning, the state of the entire five-qubit system (i.e., the teleported qubit and two EPR pairs) can be represented as

$$\begin{aligned} &\frac{1}{2}|y\rangle_{A1} \otimes (|0\rangle_{A2}|0\rangle_{C1} + |1\rangle_{A2}|1\rangle_{C1}) \\ &\qquad \otimes (|0\rangle_{C2}|0\rangle_{B1} + |1\rangle_{C2}|1\rangle_{B1}) \\ &\quad = \frac{1}{2}(\alpha|0\rangle_{A1} + \beta|1\rangle_{A1}) \\ &\qquad \otimes (|0\rangle_{A2}|0\rangle_{C1} + |1\rangle_{A2}|1\rangle_{C1}) \\ &\qquad \otimes (|0\rangle_{C2}|0\rangle_{B1} + |1\rangle_{C2}|1\rangle_{B1}) \end{aligned} \tag{7}$$

where the suffixes (e.g., $A1, A2, B1, C1, C2$, etc.) stand for the ordinal numbers at the owner's side. For example, the state with the suffix $A1$ represents *Alice's* first qubit. Similarly, *Candy's* second qubit is symbolized by the suffix $C2$.

After *Alice* and *Candy* both send their first qubits through a CNOT gate, the entire system would become

$$\begin{aligned} \frac{1}{2}[&\alpha|0\rangle_{A1} \otimes |0\rangle_{A2}|0\rangle_{C1} \otimes (|0\rangle_{C2}|0\rangle_{B1} + |1\rangle_{C2}|1\rangle_{B1}) \\ &+ \alpha|0\rangle_{A1} \otimes |1\rangle_{A2}|1\rangle_{C1} \otimes (|1\rangle_{C2}|0\rangle_{B1} + |0\rangle_{C2}|1\rangle_{B1}) \\ &+ \beta|1\rangle_{A1} \otimes |1\rangle_{A2}|0\rangle_{C1} \otimes (|0\rangle_{C2}|0\rangle_{B1} + |1\rangle_{C2}|1\rangle_{B1}) \\ &+ \beta|1\rangle_{A1} \otimes |0\rangle_{A2}|1\rangle_{C1} \otimes (|1\rangle_{C2}|0\rangle_{B1} + |0\rangle_{C2}|1\rangle_{B1})]. \end{aligned} \tag{8}$$

TABLE I
RELATION BETWEEN THE MEASUREMENT OUTCOMES AND *BOB's* QUBIT STATE

| *A*1 **XOR** *C*1 | *A*2 **XOR** *C*2 | *Bob*'s qubit state | Applied operations |
|---|---|---|---|
| 0 | 0 | $\alpha\|0\rangle + \beta\|1\rangle$ | Nothing |
| 0 | 1 | $\alpha\|1\rangle + \beta\|0\rangle$ | ***X*** gate |
| 1 | 0 | $\alpha\|0\rangle - \beta\|1\rangle$ | ***Z*** gate |
| 1 | 1 | $\alpha\|1\rangle - \beta\|0\rangle$ | Both ***X*** and ***Z*** gates |

Then, both *Alice* and *Candy* apply the *Hadamard* gate to their first qubits, and then the system would turn into

$$\begin{aligned}\frac{1}{4}&[\alpha(|0\rangle + |1\rangle)_{A1} \otimes |0\rangle_{A2} \otimes (|0\rangle + |1\rangle)_{C1}\\ &\otimes (|0\rangle_{C2}|0\rangle_{B1} + |1\rangle_{C2}|1\rangle_{B1})\\ &+ \alpha(|0\rangle + |1\rangle)_{A1} \otimes |1\rangle_{A2} \otimes (|0\rangle - |1\rangle)_{C1}\\ &\otimes (|1\rangle_{C2}|0\rangle_{B1} + |0\rangle_{C2}|1\rangle_{B1})\\ &+ \beta(|0\rangle - |1\rangle)_{A1} \otimes |1\rangle_{A2}\\ &\otimes (|0\rangle + |1\rangle)_{C1} \otimes (|0\rangle_{C2}|0\rangle_{B1} + |1\rangle_{C2}|1\rangle_{B1})\\ &+ \beta(|0\rangle - |1\rangle)_{A1} \otimes |0\rangle_{A2} \otimes (|0\rangle - |1\rangle)_{C1}\\ &\otimes (|1\rangle_{C2}|0\rangle_{B1} + |0\rangle_{C2}|1\rangle_{B1})].\end{aligned} \tag{9}$$

Expression (9) can be rewritten in the following way:

$$\begin{aligned}\frac{1}{4}&[(|0\rangle_{A1}|0\rangle_{C1} + |1\rangle_{A1}|1\rangle_{C1}) \otimes (|0\rangle_{A2}|0\rangle_{C2}\\ &+ |1\rangle_{A2}|1\rangle_{C2}) \otimes (\alpha|0\rangle + \beta|1\rangle)_{B1}\\ &+ (|0\rangle_{A1}|0\rangle_{C1} + |1\rangle_{A1}|1\rangle_{C1}) \otimes (|0\rangle_{A2}|1\rangle_{C2}\\ &+ |1\rangle_{A2}|0\rangle_{C2}) \otimes (\alpha|1\rangle + \beta|0\rangle)_{B1}\\ &+ (|0\rangle_{A1}|1\rangle_{C1} + |1\rangle_{A1}|0\rangle_{C1}) \otimes (|0\rangle_{A2}|0\rangle_{C2}\\ &+ |1\rangle_{A2}|1\rangle_{C2}) \otimes (\alpha|0\rangle - \beta|1\rangle)_{B1}\\ &+ (|0\rangle_{A1}|1\rangle_{C1} + |1\rangle_{A1}|0\rangle_{C1}) \otimes (|0\rangle_{A2}|1\rangle_{C2}\\ &+ |1\rangle_{A2}|0\rangle_{C2}) \otimes (\alpha|1\rangle - \beta|0\rangle)_{B1}].\end{aligned} \tag{10}$$

From expression (10), it can be seen that *Bob* would have the information of his qubit state once he is informed of *Alice's* two qubit states and *Candy's* two qubit states. For example, if *Alice's* two qubits are in the state $|0\rangle_{A1}|0\rangle_{A2}$ and *Candy's* two qubits are in the state $|0\rangle_{C1}|1\rangle_{C2}$, then *Bob's* qubit must be in state $\alpha|1\rangle+\beta|0\rangle$. Therefore, the measurement outcomes of these qubits have to be delivered to *Bob* through the classical channels (i.e., the doubled lines in Fig. 9).

After receiving the measurement outcomes, *Bob* can fix up his own qubit to recover $|\text{y}\rangle$ by either applying nothing, $X$ gate, $Z$ gate, or both $X$ and $Z$ gates. The relation between the measurement outcomes and *Bob's* qubit state can be found in Table I. It depicts that if: 1) the result of *Alice's* first qubit *XOR Candy's* first qubit is 0 and 2) the result of *Alice's* second qubit *XOR Candy's* qubit is 1, then *Bob* has to fix up his qubit by applying quantum $X$ gate. Likewise, if 1) the result of *Alice's* first qubit *XOR Candy's* qubit is 1 and 2) the result of *Alice's* second qubit *XOR Candy's* qubit is 0, then *Bob* can fix up his state by applying quantum $Z$ gate. The skeleton for the quantum routing mechanism is shown in Fig. 10.

By induction, it can be seen that the proposed quantum routing mechanism is able to route through more than one intermediate node. In addition, quantum circuits for the quantum routing mechanism as shown in Fig. 9 can be performed in parallelism. Consequently, the executing time of the quantum routing mechanism is approximate to that of the quantum teleportation. In other words, the data rate (qubits/s) of quantum routing mechanism is nearly identical to that of quantum teleportation. So we conclude that the quantum routing mechanism is close to optimum in data transmission rate even for the case where no EPR pair is shared between source and destination.

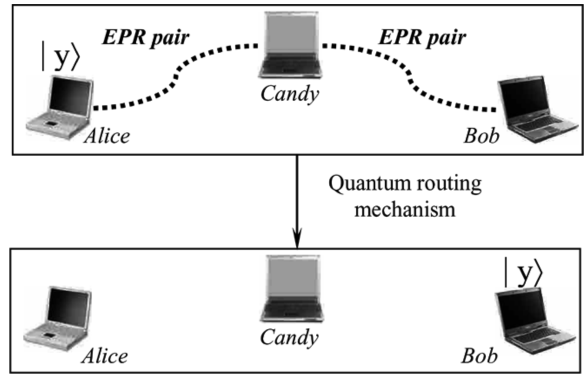


Fig. 10. Skeleton diagram for using quantum routing mechanism.

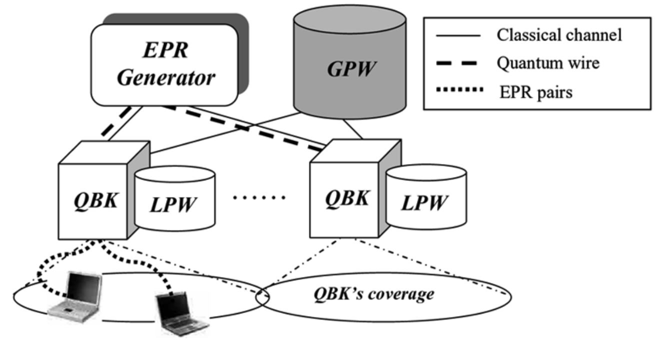


Fig. 11. Hierarchical network architecture for quantum wireless communication.

In addition, it is worth mentioning that most quantum gates in quantum routing mechanism can be performed asynchronously. Therefore, it is unnecessary to maintain time synchronization [11] between source and intermediate nodes. In other words, source and intermediate nodes do not need to coordinate before they want to perform each gate. It is because that even if the source completes its circuits before the intermediate nodes do, then the quantum routing mechanism degenerates into the quantum relay scheme. On the other hand, if the intermediate nodes complete their execution earlier than the source does, then the quantum routing mechanism degenerates into the EPR-pair bridging. From these two aspects, it can be seen that the quantum routing mechanism is made up of the quantum relay scheme and the EPR-pair bridging.

## IV. QUANTUM WIRELESS COMMUNICATION NETWORK

In this section, we focus on the wireless WAN and propose a two-tier network architecture for wireless communication in quantum domain. In addition, based on the proposed network structure, a wireless communication protocol is proposed.

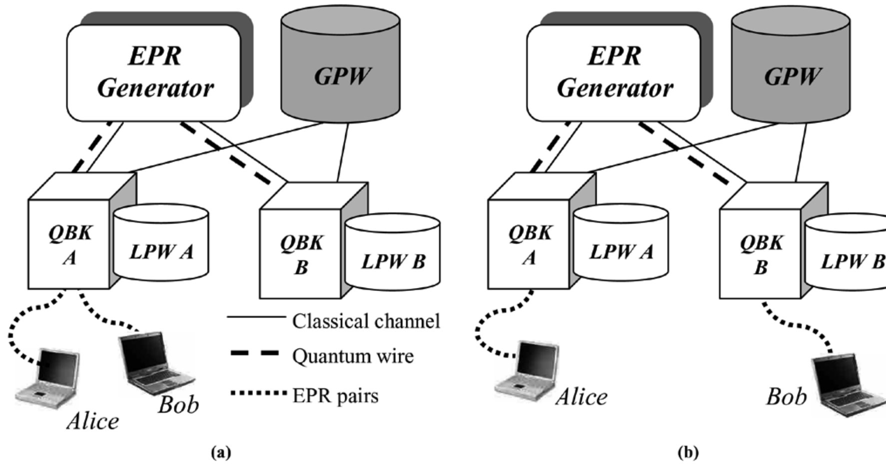


Fig. 12. Two possible cases for the location of *Bob*.

### A. Hierarchical Network Architecture

The fundamental network components in the network architecture can be roughly sketched in Fig. 11. It can be seen from Fig. 11 that one of the main components in the network is the *quantum bridge keeper* (QBK). These QBKs constitute the radio interface between the radio access and fixed network systems. Each QBK is equipped with one or more *radio transceivers* (RTs), which are used to transmit and receive classical data in the form of electromagnetic waves. Moreover, based on the maximum transmission radius of these radio transceivers, each QBK has its own effective serving coverage, which is denoted by the *QBK's coverage*.

The main purpose of the QBK is to manage EPR pairs shared with itself and mobile quantum devices that are inside its coverage. When a mobile quantum device moves into another QBK's coverage, the EPR pairs shared with the previous QBK need to devolve upon the new QBK. When a wireless quantum device inside its coverage transmits or receives a quantum state, the QBK plays the role of an intermediate node to relay the qubit.

In addition, each QBK is equipped with a regional database, *Local Position Warehouse* (LPW), to record the information of each wireless quantum device inside the QBK's coverage. LPW can also be used to determine whether a certain quantum subscriber is inside the coverage of this QBK or not.

In addition to LPWs, there exists a global database, which is called the *Global Position Warehouse* (GPW), in the core network. The main purpose of the GPW is to manage the location information of all mobile quantum devices. It records the current location of all quantum mobile devices. By inquiring the GPW, one can find out which QBK's coverage a specific wireless quantum device is in. Thus, the data stored in the GPW needs to be updated frequently. In other words, as long as a quantum mobile device moves from one QBK's coverage into another QBKs, the data in the GPW shall be updated synchronously so that it keeps the current location of all wireless quantum devices.

The EPR generator is included in the network infrastructure as well. The EPR generator is responsible for generating EPR pairs. Once two QBKs need to set up a quantum channel for the devices under their coverage, the EPR generator would distribute the generated EPR pair by sending one qubit to one QBK and the other qubit to the other QBK by quantum wires. It can be seen from Fig. 11 that quantum wires are shown between each QBK and the EPR generator.

Each mobile quantum device is assigned to a *home QBK* with which the mobile device shares a lot of EPR pairs initially. Furthermore, in order to transmit/receive the classical data to/from the QBKs through the air, each quantum device is also equipped with an antenna so that it can transmit and receive classic data in the form of electromagnetic waves. When a mobile device roams to the coverage area of another QBK, a handoff scheme is required to update the location of the quantum device and to set up the entanglement-assisted quantum channel between the device and the new QBK. The issues of the handoff scheme will be discussed in Section V.

### B. Quantum Wireless Communication Protocol

Consider the scenario in which a wireless quantum device, *Alice*, would like to deliver a qubit to another wireless quantum device, *Bob*. In the beginning, *Alice* who is inside the coverage of QBK $A$ sends a request to notify QBK $A$ that *Alice* wants to teleport a quantum state to *Bob*. Then, QBK $A$ would query its own LPW to check whether *Bob* is inside its coverage. Two possible cases may occur afterwards.

*Case 1:* *Bob* is inside the coverage of QBK $A$, as shown in Fig. 12(a).

Namely, *Bob* also shares EPR pairs with QBK $A$. In this case, QBK $A$ plays the role of the intermediate node between *Alice* and *Bob*. Therefore, after applying the quantum routing mechanism with routing path *Alice* $\rightarrow$ QBK $A \rightarrow$ *Bob*, the qubit transmission would be achieved. The quantum circuits for this case is shown in Fig. 13.

*Case 2:* *Bob* is not inside the coverage of QBK $A$, as shown in Fig. 12(b).

In this case, QBK $A$ would inquire the GPW to determine which QBK *Bob* resides in. The GPW would respond to QBK $A$ that *Bob* is inside the coverage of QBK $B$. Then, QBK $A$ asks the EPR generator to set up an EPR pair between QBK $A$ and QBK $B$. Afterwards, the EPR generator would distribute

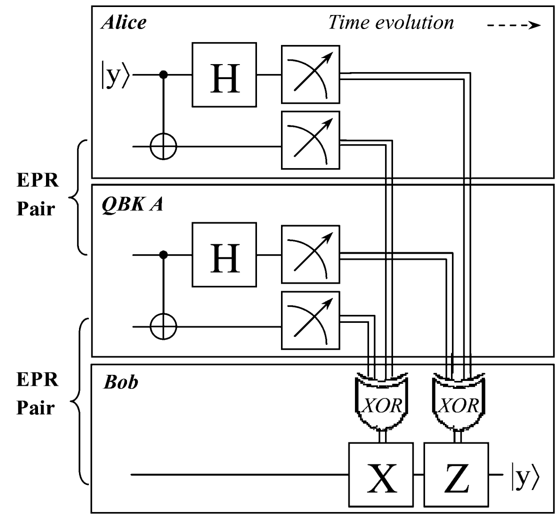


Fig. 13. Quantum circuits for the case that *Alice* and *Bob* are within the same QBK's coverage.

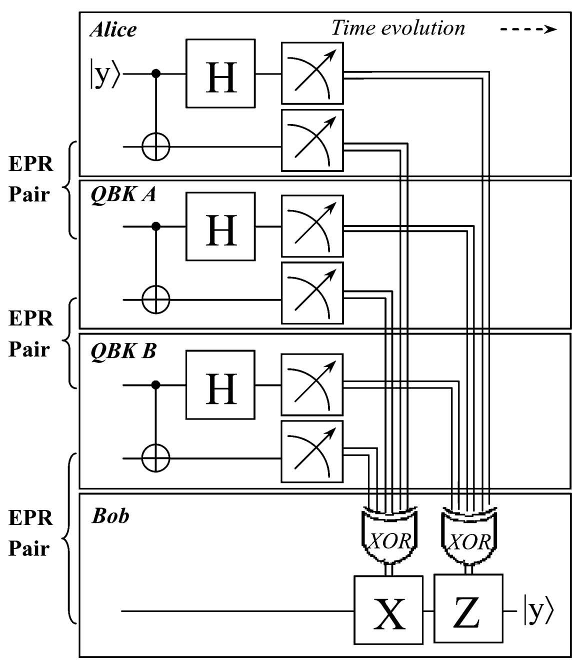


Fig. 14. Quantum circuits for the case that *Alice* and *Bob* are under the coverage of different QBKs.

an EPR pair by sending one qubit to QBK $A$ and transporting the other qubit to QBK $B$. After QBK $A$ and QBK $B$ receive the qubits from the EPR generator, they serve as the intermediate nodes between *Alice* and *Bob* together. Consequently, after performing the quantum routing mechanism with routing path *Alice* $\rightarrow$ QBK $A$ $\rightarrow$ QBK $B$ $\rightarrow$ *Bob*, the qubit transmission would also be carried out. The quantum circuits for this case are shown in Fig. 14.

On the other hand, it reveals that some of the existing RRM strategies (e.g., handover strategy) for wireless WAN need to be investigated in order to enhance the new wireless communication protocol. As a result, in the next section, we discuss these emerging problems and also present possible solutions to these problems.

## V. Discussion

In this paper, a quantum routing mechanism is proposed. In addition, network architecture is developed to establish a new quantum wireless communication infrastructure. Nevertheless, there are still many open problems remaining. In this section, we list out some open problems and discuss how to tackle them briefly.

### A. EPR Pair Supplement

As mentioned above, the EPR pair plays an important role to perform quantum teleportation and quantum routing mechanism. EPR pairs will be consumed each time a quantum routing is performed. However, due to wireless connectivity, a quantum mobile device cannot be supplemented with EPR pairs at all times. As a result, it might fail to perform the quantum wireless communication because of using up the EPR pairs. Therefore, quantum mobile stations require another charging device to supply EPR pairs. In other words, EPR pairs just like the traditional battery shall be considered as a type of precious resource.

### B. Routing Path Exploration and Maintenance

The proposed network architecture is primarily for quantum wireless WAN. However, for other categories of wireless communication networks such as wireless local area networks (LANs) and personal area networks (PANs), the proposed quantum routing mechanism still can work. But for those wireless technologies, the network component such as the QBK in wireless WAN is not required to record the mobile devices' positions. Instead, a routing path shall be explored when a mobile device would like to transmit data wirelessly.

In literature, many routing path exploration schemes have been reported [14], [17]. However, most of them are not suitable for the quantum-domain routing. It is because the traditional schemes prefer to probing the shortest routing paths. On the contrary, based on the results presented in Section III, the data transmission time by applying the proposed quantum routing mechanism is independent of the number of routing hops. Therefore, unlike the conventional routing path exploration mechanisms that prefer to taking the shortest paths, quantum routing will take the number of remaining EPR pairs into the consideration. For example, suppose there exist two routing paths from mobile device *Alice* to *Bob*. One of them is *Alice* $\rightarrow$ *Candy* $\rightarrow$ *Bob* and the other is *Alice* $\rightarrow$ *David* $\rightarrow$ *Eric* $\rightarrow$ *Bob*. Even though the former routing path is shorter, the number of the remaining EPR pairs in *Candy* is so small that it might fail to communicate with others due to the shortage of EPR pairs. Therefore, the latter path (with longer length) will be picked instead.

### C. Handover Scheme Modification

One of the purposes of the QBK is to have the custody of EPR pairs. When a wireless quantum device moves into another QBK's coverage, it needs to acquire the EPR pairs shared with the new QBK. This issue can be tackled by utilizing the proposed EPR-pair bridging. For example, suppose that a quantum mobile device that shares $n$ EPR pairs with QBK $A$ moves to the coverage of QBK $B$. Then, QBK $A$ asks the EPR generator to establish $n$ EPR pairs between QBK $A$ and QBK $B$. After that, QBK $A$ performs the EPR-pair bridging so as to deliver the $n$ qubits, which are entangled with the qubits in the quantum mobile device, to QBK $B$. Afterwards, the quantum mobile device would share $n$ EPR pairs with QBK $B$.

## VI. Conclusion

This paper represents the first work to investigate the issue about wireless communication for mobile devices in the quantum domain. This paper proposes a quantum routing mechanism, which enables a quantum mobile device to teleport a quantum state to a remote site even if they do not share EPR pairs mutually. In terms of the time complexity, the time that quantum routing mechanism takes to teleport a quantum state is independent of the number of routing hops. From this aspect, the proposed quantum routing mechanism is close to optimum in data transmission time. In addition, in order to establish a quantum communication infrastructure, this paper also presents a network architecture for wireless WAN. This architecture is scalable and its corresponding communication protocol is developed as well.

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