Ring-Based Quantum Network with Quantum Key Distribution (QKD) and Quantum Digital Signature (QDS)

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Abstract. Quantum technological developments offers a great promise for implementing secure quantum internet. In this study, we propose a ring topology-based quantum network with QKD and QDS for the quantum internet. The combination of QKD and QDS allows both the detection of the intruder and the increase in security in the network. The proposed network has been demonstrated to work by being implemented in the SQUANCH network simulator [1].

Keywords: quantum internet, ring-based quantum network, quantum key key distribution

1. Introduction

Superior features of quantum technology such as entanglement and superposition enable teleportation and super-dense coding. In addition to these, when the feature that it is impossible to measure a feature of a system without changing its state, the superiority of quantum technologies over classical technologies becomes clear. These superior features not only offer many opportunities to humanity, but also offer secure communication. In recent years, scientists have developed quantum key generation devices that enable secure communication and have used them in practice. In this context, long-distance QKD networks with reliable nodes are also currently possible [2–5]. Recently, the distance of 500 km has been achieved on fibre based channels [6]. Similarly, the applications of entangled interaction between quantum memories in recent years show that the quantum internet can be applied in the very near future [7]. For example, countries such as China [8,9], European countries [10–12] and America [13] invest heavily in the quantum internet. Recently, satellite-based quantum internet applications have been developed by many countries such as China, America, Canada, Japan, Singapore
and Europe to carry the quantum internet to longer distances \cite{14–20}. In this study, we propose a quantum network based on a central network topology consisting of nested rings. Since this network uses both QKD and QDS, it offers a more secure quantum internet opportunity. The paper is organized as follows: In Section 2, the structure of Ring Based Quantum Network Topology is given. Also quantum communication on the suggested network is explained with example. In Section 3, implementation of Ring-Based Quantum Network with QKD and QDS is given. In Section 4 concludes the article.

2. Ring Based Quantum Network Topology

In this study, the quantum Internet is modelled as a ring-based quantum network consisting of quantum nodes, repeaters and channels. Since the quantum network will be long distance, there should be quantum repeaters at certain intervals between the nodes. Each nodes consist quantum devices and classic controlled agent devices. These quantum devices will be able to create qubits, apply some quantum transformations and have acceptable error rates. In addition to this, classic controlled agent devices can do classical work on all nodes. All this is shown in Figure 1 below.

![Ring Based Quantum Network Topology](image)

**Figure 1:** An example of nodes and channels in a ring-based network topology.

There is a central node, as can be seen in Figure 1. This is the zero ring. Other nodes are opened ring-by-ring on it. Each node in a ring is connected by quantum channels with the nearest nodes up to the degree of the ring. Classical channels between all nodes in the network can be arranged as desired. Let’s examine how communication takes place on the proposed topology. For this purpose, let’s consider a cross-section of the mesh as in Figure 2.
The communication between Alice and Bob over the proposed ring-based quantum network takes place as follows.

- Alice’s Key Generation
- Generation of Sign as Key
- Alice Inherits Sign as Key
- Alice Prepares the Message
- Bob Handles Message
- Decryption of Message
- Return of Message Pieces

a-) Alice’s Key Generation

The communication is start with generic quantum key distribution process. Alice and Bob runs an quantum key generation protocol between themselves. After a successful run of protocol both party generates the $S_{AB}$ key. If this protocol ends with no success Alice prepares and sends an error report to center node. Table 1 is holds current knowledge of nodes.

Table 1: Knowledge table after step 1.

| Alice | Bob | 0   | 1   | 2   | C   |
|-------|-----|-----|-----|-----|-----|
| $S_{AB}$ | $S_{AB}$ | -   | -   | -   | -   |

b-) Generation of Sign as Key

Alice now needs keys for encryption other than generated key. Alice request signs from the connected sub-level nodes. Sub-level nodes must holds an generated sign from center
node. If these sub-level nodes grade low enough to hold original sign then they request a generated sign from center node. Else they inherit the signs from one of connected sub-level nodes. In this example "0", "1" and "2" named nodes grade is 1 which is low enough to hold original signs from center node. So they contact to center node for getting these sign. After successful quantum key distribution process between "0" to center and "1" to center $S_{C0}$ and $S_{C1}$ keys are generated. Center node generates unique $M_0$ and $M_1$ signs then encrypts them with related keys from QKD protocol. Center node sends $V_{C0} = S_{C0}(M_0)$ and $V_{C1} = S_{C1}(M_1)$ information to related nodes.

Table 2: Knowledge table after step 2.

| Alice | Bob | 0   | 1   | 2   | C  |
|-------|-----|-----|-----|-----|----|
| $S_{AB}$ | $S_{AB}$ | -   | -   | -   | -  |
| -     | -   | $V_{C0}$ | $V_{C1}$ | -   | $M_0$, $M_1$ |

c-) Alice Inherits Sign as Key

In this stage Alice inherit encrypted sign as keys from connected low-level nodes. These signs was generated in previous step. With the success of QKD protocol, inherit communication process happens.

Table 3: Knowledge table after step 3.

| Alice | Bob | 0   | 1   | 2   | C  |
|-------|-----|-----|-----|-----|----|
| $S_{AB}$ | $S_{AB}$ | -   | -   | -   | -  |
| -     | -   | $V_{C0}$ | $V_{C1}$ | -   | $M_0$, $M_1$ |
| $V_{C0}$, $V_{C1}$ |  | -   | -   | -   | -  |

d-) Alice Prepares the Message

In this step Alice processes the $K$ message she wants to send. Alice then selects an partition method $B$ from the partition method pool which designed for the topology. Alice then divides the message as $K = K_0 + K_1 + ... + K_n$ with the selected method. $n$ is equal to degree of the Alice in topology. Alice encrypts every piece of the message with encrypted sign as keys that she was got and translates them into $F = V(K)$. Alice then prepares package $P$ containing partition method, connected low-level node identifications and message $F$. Alice encrypts the $P$ package with $S_{AB}$ and translate $P$ into $P' = S_{AB}(P)$. Lastly Alice sends $P'$ to Bob.
Table 4: Knowledge table after step 4.

| Alice | Bob | 0 | 1 | 2 | C |
|-------|-----|---|---|---|---|
| $S_{AB}$ | $S_{AB}$ | - | - | - | - |
| - | - | $V_{C0}$ | $V_{C1}$ | - | $M_0, M_1$ |
| $V_{C0}, V_{C1}$ | - | - | - | - | - |
| $P, K$ | $P'$ | - | - | - | - |

$e)$ Bob Handles Message

Bob runs successful QKD protocol with each of connected nodes from low-level ring after Bob decrypts $P'$ package and extract $P$ information. Bob sends them every piece of message $F$ with using generated keys. If node identification in package $P$ matches with one of node from Bob’s connected nodes, Bob sends related piece of message to them. In this example Bob sends $F0$ piece to node ”2” and $F1$ piece to node ”1”. Bob also sends them identification of nodes with related piece because target nodes needs to verify if they are bequeath of sign.

Table 5: Knowledge table after step 5.

| Alice | Bob | 0 | 1 | 2 | C |
|-------|-----|---|---|---|---|
| $S_{AB}$ | $S_{AB}$ | - | - | - | - |
| - | - | $V_{C0}$ | $V_{C1}$ | - | $M_0, M_1$ |
| $V_{C0}, V_{C1}$ | - | - | - | - | - |
| $P, K$ | $P'$ | - | - | - | - |
| - | - | - | $F0, node1$ | $F1, node0$ | - |

$f)$ Decryption of Message

The low-level nodes who got message from Bob tries decrypts the message. If related node identification matches with themselves they decrypts piece of message $F_n$ with its encrypted sign as key $V_n$ and extracts the piece of real message $K_n$. If match process returns false then sends them to low-level nodes until any identification match happens. At the worst case scenario piece of message reaches center node and center node decrypts the piece of massage. Since center node only one sign provider of network he knows all signs exits on whole network.
Table 6: Knowledge table after step 6.

| Alice | Bob | 0   | 1   | 2   | C   |
|-------|-----|-----|-----|-----|-----|
| \( S_{AB} \) | \( S_{AB} \) | -   | -   | -   | -   |
| -     | -   | \( V_{C0} \) | \( V_{C1} \) | -   | \( M_0, M_1 \) |
| \( V_{C0}, V_{C1} \) | -   | -   | -   | -   | -   |
| \( P, K \) | \( P' \) | -   | -   | -   | -   |
| -     | -   | -   | \( F_0, \text{node}0 \) | \( F_1, \text{node}0 \) | -   |
| -     | -   | -   | \( K_0 \) | -   | \( K_1 \) |

\( g) \) Return of Message Pieces

In this final step every piece of message that decrypted returns to Bob. Bob easily gather all pieces he got since he know partition method \( B \) and reaches the \( K \) message. Alice and Bob agrees upon a successful communication and reports the whole process to center node. As we demonstrated an example communication; all protocol about is splitting and encrypting message while other party tries to recover the message with the helps from other nodes.

Table 7: Knowledge table after step 7.

| Alice | Bob | 0   | 1   | 2   | C   |
|-------|-----|-----|-----|-----|-----|
| \( S_{AB} \) | \( S_{AB} \) | -   | -   | -   | -   |
| -     | -   | \( V_{C0} \) | \( V_{C1} \) | -   | \( M_0, M_1 \) |
| \( V_{C0}, V_{C1} \) | -   | -   | -   | -   | -   |
| \( P, K \) | \( P' \) | -   | -   | -   | -   |
| -     | -   | -   | \( F_0, \text{node}1 \) | \( F_1, \text{node}0 \) | -   |
| -     | -   | -   | \( K_0 \) | -   | \( K_1 \) |

3. Implementation of Ring-Based Quantum Network with QKD and QDS on SQUANCH

SQUANCH is simple quantum node and channel simulation framework written in Python. This framework allows us to simulate quantum networks. While SQUANCH unfortunately allows only few nodes for reasonable simulation, it sure runs fast among the other tools. We coded the same network in Figure 3 with SQUACNH and run the exact same example we gave previous section.
4. Conclusion

In this article, we study a ring topology-based quantum network with QKD and QDS for the quantum internet. We implemented the purposed network in the SQUANCH network simulator.

We will discuss about security on the suggested topology. While all nodes must run QKD protocol for any communication but we always thought QKD is penetrable protocol. The first aim is about how to always check for observers.

In the suggested topology first two ring of network should locally close to center nodes and always supervise. We prefer other rings expand exponential in distance since we wanted to maximize security for long distance. The nodes of first two ring should able to hold original signs from center node and their count in their ring also should lower than any ring in topology.

The other topic would be about generation of signs. Center node should never
generate same sign from past. Sign holder nodes should throw old signs as new request made. Center node only approver of sign other then sign holder.

The other subject we need to discuss about is partition method of messages. We imagine dynamic and huge pool for partition methods. Center node should handle all syncing these pool over whole topology. In addition to classical complexity we prefer a dummy message to start a new communication between nodes.

The topology in our work may appear to much centralized but in the any communication other party nodes never gets the complete of message. Even in worst case scenario where center node decrypts all piece of message center node do not know partition method.

Attacker must penetrate QKD protocol and doing this for all channels of a target node. But being success with this method also drops if attacker tries to listen a high-level ring node since that node have much higher channel count. Attacker should perfectly listen \( n+1 \) quantum channel for a success penetration. Also success depends on attacker knows message partition method.

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