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# Hybrid routing protocol for quantum network based on classical and quantum routing metrics

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**ABSTRACT**

A quantum repeater is the heart of a quantum internet that enables end-to-end communication over long distances using the quantum entanglement feature. Although this characteristic gives quantum networks tremendous power in terms of speed and security, it puts quantum networks, especially the quantum internet, in front of challenges, like transforming a short-distance quantum link into a long-distance link, in addition to entanglement routing for finding the best path within a quantum network. So, this research aims to propose a hybrid quantum routing protocol (HQRP) based on routing metrics of the classical networks like hops count, as well as metrics of the quantum network represented by the possibility of entanglement between end nodes in the network. As a result, a mathematical model was built to determine the optimal path among many paths within the quantum network, and it was implemented on our quantum network simulator. Finally, we concluded that the proposed algorithm gives the optimal path based on the highest entanglement probability and lowest number of hop count.

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## 1. INTRODUCTION

The Quantum information is generated, processed, and transmitted by quantum processors and repeaters that are connected to each other to form a quantum network [1], [2]. Quantum network's primary task is delivering this information between parts of the network in a safe and fast manner the quantum network's means are mainly based on the quantum mechanics [3].

Quantum internet is the most promising future of the current internet and is characterized by its strength, as the reason for this strength is due to the property of quantum entanglement, which is one of the properties of quantum physics to which the quantum internet is subject to [2], [4]. However, the property of quantum entanglement has enabled many applications that are difficult to implement in classical networks such as clock synchronization, quantum key distribution (like BB84 [5]–[7]) [8], secure long-distance communication, and distributed quantum computing [9], [10]. However, the improvement of communication technologies is the responsibility of quantum networks [11], as the classical networks are not canceled by the emergence of quantum networks in the wide range, but instead, the principles of both classical and quantum communication gave an ideal combination, which is quantum communication [12], [13]. On the other hand, the performance of quantum networks depends on two basic parameters which are the rate of entanglement generation and the rate of time for decoherence of entangled quantum bits between quantum memories [14].

Despite these capabilities of quantum networks, the entanglement feature, which gave power to these networks, opens new challenges to this field, such as the time of decoherence as well as the distribution of entangled qubits [15], [16]. The challenges will not be satisfied with this limit but will continue to the possibility of transforming short-distance entanglement into long-distance entanglement, as it is considered a key challenge for the quantum internet because the transmission of quantum data over the network is done through the property of quantum entanglement between the memories of quantum devices in a work called teleportation [2], [17], [18].

In addition, the routing of information i.e., finding the best path among several paths between the sender and the receiver within quantum networks is one of the challenges that the researchers tried to find solutions to [19]. Where the researches [9] suggested two new algorithms for routing within the ring topology of a quantum network by adopting different measures in each algorithm for routing within the network, where the number of rings with distance and the possibility of entanglement with distance were used in the two algorithms respectively and as a result, it was concluded that the second algorithm gives better results than the first algorithm, where the entanglement rate between quantum bits in quantum memories was higher than in the first algorithm, as the entanglement rate is the basis for quantum routing of quantum data. While the current knowledge of network topology, location of end-user, and current link state knowledge are the metrics in the routing algorithm that was presented in the researches [10], where this research found that the end-to-end entanglement rate-that resulting from the local quantum entanglement swap procedure after the command issued by the quantum nodes-is higher in the network than when the global knowledge of the network is relied upon, while the local knowledge has a low entanglement rate, and whenever the entanglement rate is high in one of the paths, it will be preferred over the other. On the other hand, the time required to establish the connection between nodes in addition to the number of messages required to be exchanged between nodes for the purpose of completing the establishment of the connection was reduced to a certain level when the researches [20] presented a protocol that includes a hybrid metric of both the classical network route metrics and the quantum network metric for a wireless ad hoc network quantum. Also, the researches [2] is due to the adoption of the throughput, which is represented by the entanglement rate as a metric of routing in the quantum network, but differently from what was presented in the paper [9]. An algorithm called quantitative competitive allele-specific taqman (Q-CAST) was built, where it depends at the origin of its work on the presence of several paths between the sender and the recipient, which are determined using the global view in the network, where two classical routing algorithms, namely Greedy and Dijkstra are used to determine the shortest path and then build quantum entanglement within these paths, finally the highest throughput path is the best path. While both studies [21], [22] relied on the use of special quantum states called graph-states, where the first one used this type of quantum state for routing within the regional level of the quantum network, it was assumed that the quantum router is a common part between a number of regional networks, as well as using two classical algorithms for the purpose of determining the shortest path, these two algorithms are Dijkstra and the Steiner trees, where the cost used in this algorithms depends on the type of application such as the quantum states that are consumed, and therefore the reliability was achieved within the proposed algorithms. On the other hand, for this method (using graph-states), the researches [22] achieved end-to-end quantum entanglement, and the effort imposed on the quantum repeater for the purpose of conducting the measurement was reduced, so that the time required to establish the quantum path was also reduced.

This research aims to suggest a hybrid quantum routing protocol (HQRP) that finds the optimal path between several paths within the quantum network to send quantum information in a fast, safe, and reliable manner based on a classical metric such as hop count and quantum metric which is the possibility of a quantum link between end nodes. This paper presents a new routing algorithm for quantum networks, as this algorithm helps the quantum repeater to make a routing decision, where the best end-to-end quantum path is determined among a number of existing paths between the sender and the recipient within the network also, implement that protocol on our quantum network simulator to verify the effectiveness of the proposed protocol. This section dealt with an overview of quantum networks and the most prominent challenges in them, in addition to that, the closest previous research to this work was presented, also, this section has clarified the objective of this research and the actual contribution to it. Section 2 describes the proposed method for routing within quantum networks in terms of the mathematical model and the simulator that was built to implement the proposed protocol. Finally, the conclusions of this work are clarified in section 3.

## 2. METHOD OF ROUTING ON THE QUANTUM REPEATER

In the previous section, the proposed algorithms, and protocols within research in the field of routing in quantum networks were described, where they are used in the generation, distribution, and swapping of entanglement to complete the work of the quantum repeater protocol. For performing routing and finding the optimal path within the quantum network over a quantum repeater device, which performs the decision-making process within the network [2] we propose a mathematical model based on several metrics represented in the probability of entanglement and hop count. Figure 1 shows the proposed flowchart. We calculate the probability of success of an end-to-end entanglement link between the sender and the recipient, then decide the best path according to the highest probability of success with the lowest hop count, where the quantum link is formed over the best path.

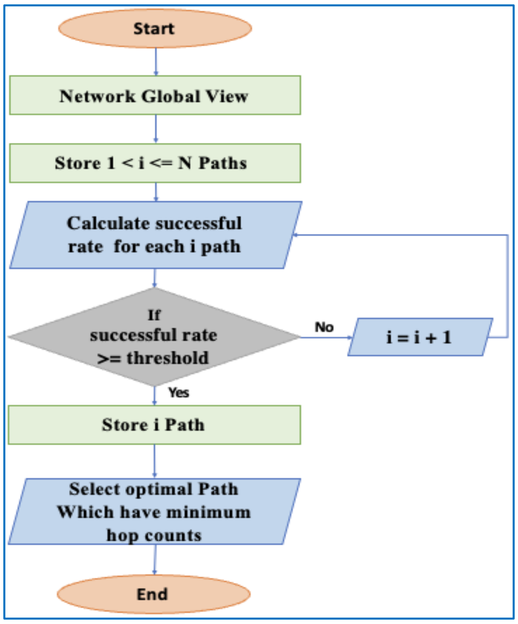


Figure 1. The proposed HQRP flowchart

### 2.1. The main idea of the proposed hybrid quantum routing protocol (HQRP)

To calculate the probability of success of an end-to-end entanglement link in Figure 2, first:

- A quantum network consists of a graph (G) containing many nodes (v) that represent quantum devices in addition to the presence of an optical fiber quantum link (E) between every two neighboring nodes in the network as shown in Figure 1.
- For every two adjacent nodes in this network a distance (d), which represents the length of optical fiber that connects two entanglement-based quantum devices, where the distance ranges (1-100 km) relative to the two studies [11], [23], where the highest distance for the distribution of entanglement was recorded to about 100 km.

Thus, the probability p (x) of finding an entanglement link between the two adjacent nodes separated by (d) distance can be found through in (1) [24], [25]:

$$p(x) = \frac{1}{2}\,(p_{th}.\eta_h.\eta_t)^2.e^{-\frac{d}{do}} \tag{1}$$

whereas $p\,(x)$ represents the probability of successful link formation between every two nodes (link-entanglement probability as represented in Figure 1) along the path from sender to receiver. where this probability is affected by:

- Entangled quantum bits that are generated within each node with a probability $p_{th}$.
- The efficiency of the detector at both heralding and telecom wavelength, which are $\eta_h$, $\eta_t$ respectively.
- The distance between every two adjacent nodes d so that the probability decreases exponentially with the increase of this distance.
- The fiber optical attenuation length $d_o$.

Each of $p_{th}$, $\eta_h$ , and $\eta_t$ will be considered constant values at each node within the quantum network. Then, the probability of a long-distance quantum link p (path) can be found by calculating the total successful rate Retotal using the reliability system: first, we calculate the failure rate of each link cdf (x) between two adjacent nodes along the path between the sender and the receiver during a period t as in (2):

$$cdf(x) = \int_0^t \big(p(x)\big)\, dt \tag{2}$$

whereas t represents the entanglement decoherence time between quantum memories (the highest decoherence time has been recorded to the present with approximately 1.46 sec using the Nitrogen-vacancy center [2], [12], [23]). however, in the case that the failure rate is high, the diamond atoms must be reset and several attempts are made to obtain a high entanglement rate (this function is attributed to the physical layer) [12].

Secondly, according to the (3), we can find the success rate Re (x) of each link between two adjacent nodes:

$$Re(x) = 1 - cdf(x) \tag{3}$$

then, to find the total reliability, retotal of that route we use the reliability system type of series-connected elements through in the (4):

$$Re_{total} = Re(x1) * Re(x2) * Re(x3) * \ldots * Re(xn) \tag{4}$$

where the x (1 to n) represents links along the path.

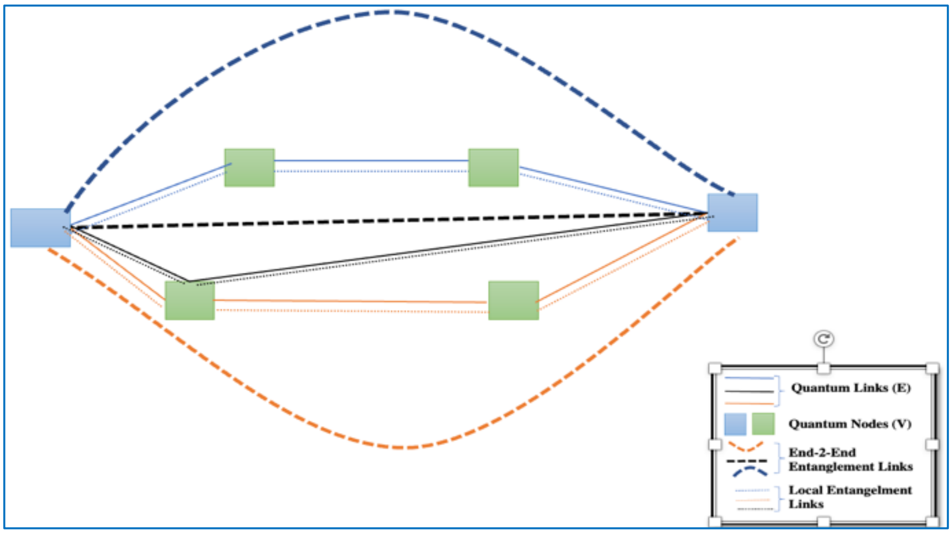


Figure 2. A quantum network components

## 2.2. Implementing the hybrid quantum routing protocol

For the purpose of verifying the work of the proposed protocol model, we apply the proposed protocol in our simulator by assigning it to each node in the quantum network, on different topologies to find the best path between many paths from sender to receiver. For example, we use the sender (repeater2) and receiver (repeater4) as shown in Figure 3. The pseudocode of the proposed protocol is shown in Algorithm 1.

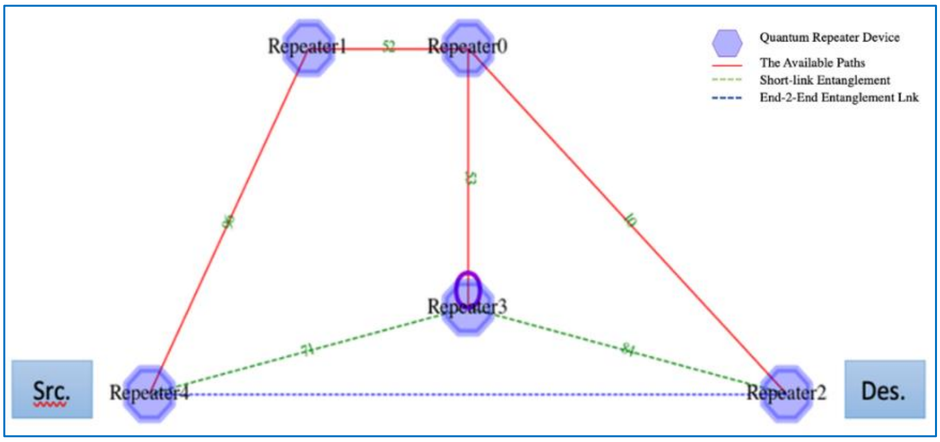


Figure 3. Applying HQRP in quantum network simulator

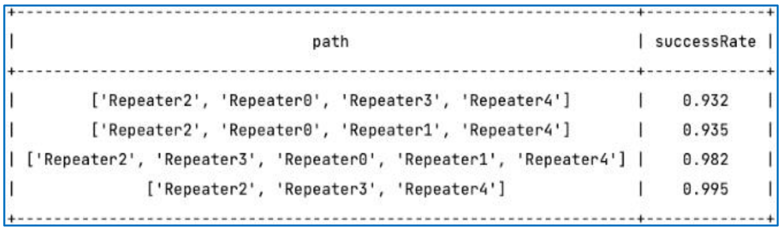
**Algorithm 1: The hybrid quantum routing protocol (HQRP)**

```
Input: List of all paths from source to destination (L), List of the distance
       between every two adjacent nodes (d)
Output: The optimal path that has the highest probability

//define the constant values
$p_{th}$← generation probability of entangled bits
$\eta_h$=$\eta_t$← detector efficiency
$d_o$← fiber optical attenuation
t← entanglement's decoherence time

//initialize empty lists
Link_success_rate← List of the success rate of each link
Path_success_rate← List of the success rate of E-2-E Link
Accepted_path← List of the accepted paths
AcceptedPath_success_rate← List of the success rate for accepted paths

//initialize the process
heighest_prob← zero
success_rate_threshold← zero
p← path in list L
E← link between two adjacent nodes in p
c← multiply of $\eta_h$, $\eta_t$, and $p_{th}$

For each p in L:
    For each E in p:
        //Calculate the success rate for each link
        Re-x=1-($\frac{1}{2}$ $c^2$. t. $e^{-d/do}$)
        Link_success_rate.append(Re-x)

    For each Re-x in Link_success_rate:
        //find Total Reliability for the End-2-End Entanglement link
        Rt= Rt* Re-x
        Path_success_rate.append (Rt)

// check the path validity
For each Rt in Path_success_rate:
    If Rt > or = 0.5
        AcceptedPath_success_rate.append(Rt)
        Accepted_path.append(the path that have this Rt)
    Else: continue

//Find the threshold of the success_rate for accepted paths
success_rate_threshold=average (AcceptedPath_success_rate)

////initialize the selection of optimal path
For each path, srate in Accepted_path, AcceptedPath_success_rate:
    If srate > success_prob_threshold and leng(path)= min(length in Accepted_path)
        Select the path as optimal path
    Else: continue
```

## 3. RESULTS AND DISCUSSION

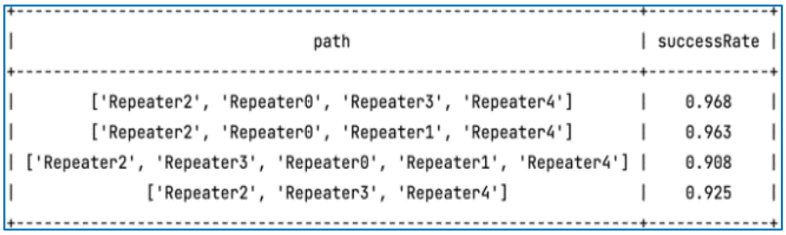
Relying on the global knowledge about the network, which is done through the classic Internet, the proposed protocol calculates quantum entanglement probabilities for each of the paths in the network implemented in the previous section as shown in Figure 4. The entanglement probabilities are stored until the entangled states are decohere we find that there are four paths from sender to receiver with an entanglement successful rate between (0.932-0.995) with a threshold of (0.961) and hop count between (1-3) hops. So, the protocol chooses a path with a probability above the threshold and minimum hop count, where the optimal path is the path that has a success rate of (0.995) with only one hop count. In case the number of hops within the paths is equal, the proposed protocol decides the best path based on the highest probability between them, which is also higher than the threshold as presented in Figure 5. From Figure 5 it can be seen that the threshold of success rate for paths is (0.941), thus, the two paths available were the same number of hops, so the best path is the one with the highest probability which is (0.968). On the other hand, to ensure the effective performance of the proposed protocol, it has been applied to the different topologies as clarified in Figure 6, and the result of applying the HQRP protocol is shown in Table 1.

It is clear from Table 1 that the performance of the proposed protocol on different topologies is effective. Where, in both topologies, the best path was chosen as the path with the highest probability with fewer hops count. As well as, Figure 7 represents the result of applying our protocol on the same network topology but at different distances between nodes, it can be seen that the probability is affected by distance as mentioned in section 2.1, also the optimal path had the highest probability with the lowest hup count.



```
+-----------------------------------------------------------------+-------------+
|                              path                               | successRate |
+-----------------------------------------------------------------+-------------+
|        ['Repeater2', 'Repeater0', 'Repeater3', 'Repeater4']      |    0.932    |
|        ['Repeater2', 'Repeater0', 'Repeater1', 'Repeater4']      |    0.935    |
| ['Repeater2', 'Repeater3', 'Repeater0', 'Repeater1', 'Repeater4'] |    0.982    |
|               ['Repeater2', 'Repeater3', 'Repeater4']            |    0.995    |
+-----------------------------------------------------------------+-------------+
```

Figure 4. The paths and their entanglement probabilities



```
+-----------------------------------------------------------------+-------------+
|                              path                               | successRate |
+-----------------------------------------------------------------+-------------+
|        ['Repeater2', 'Repeater0', 'Repeater3', 'Repeater4']      |    0.968    |
|        ['Repeater2', 'Repeater0', 'Repeater1', 'Repeater4']      |    0.963    |
| ['Repeater2', 'Repeater3', 'Repeater0', 'Repeater1', 'Repeater4'] |    0.908    |
|               ['Repeater2', 'Repeater3', 'Repeater4']            |    0.925    |
+-----------------------------------------------------------------+-------------+
```

Figure 5. The paths and their entanglement probabilities in the case of the number of hops within the paths are equal

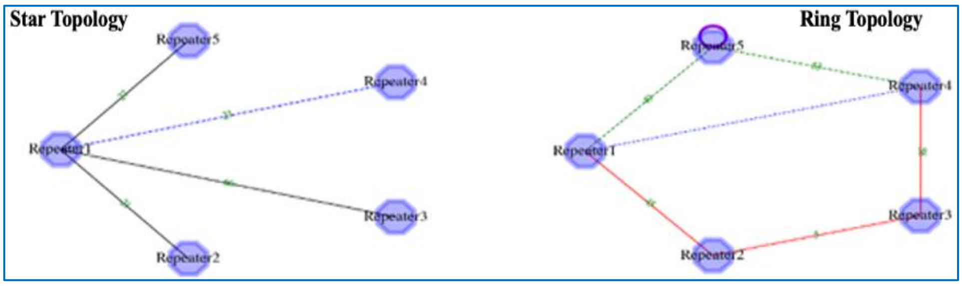


Figure 6. Applying the HQRP to different topologies

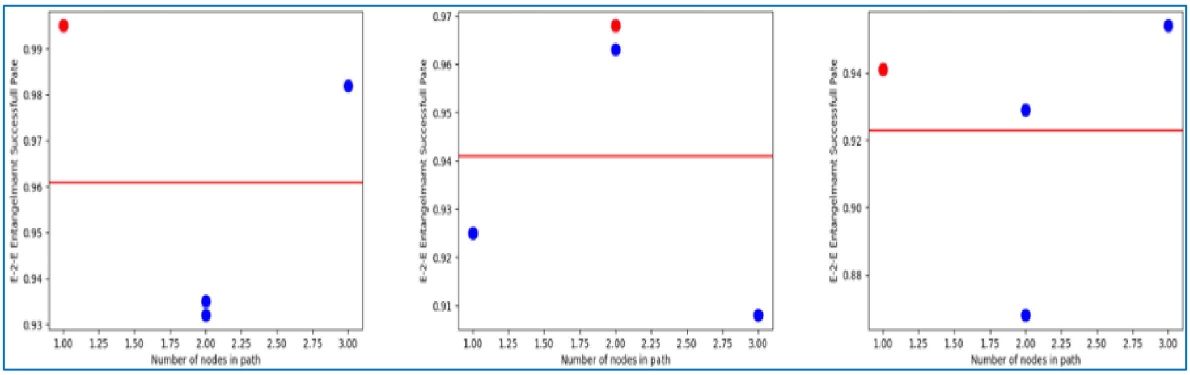


Figure 7. Applying HQRRP on the same network topology but at a different distance (the red circle represents the optimal path while the blue represents all available paths, and the red line is the success rate threshold)

Table 1. Result of applying the HQRP to different topology

| Parameters | Star topology | Ring topology |
|---|---|---|
| Available paths | Repeater1-Repeater4 | Repeater1-Repeater5-Repeater4<br>Repeater1-Repeater2-Repeater3-Repeater4 |
| Path probability | 0.969 | 0.91<br>0.982 |
| Probability threshold | 0.969 | 0.946 |
| Optimal path | Repeater1-Repeater4 | Repeater1-Repeater2-Repeater4 |

Finally, we compare our proposed HQRP with the most relevant studies in this field, as presented in Table 2 where the most important differences and similarities between them are clarified. From Table 2 we can find that the entanglement rate routing metric is used in [2], [7] and in our protocol, but in a completely different manner where, in HQRP this metric is used in combination with hop count for creating a hybrid quantum routing metric, on other hand, The proposed protocol implemented within a quantum network simulator with graphical interfaces, which allows the developer to easily deal with it and could see the results in a more accurate and detailed manner, while none of the other protocols were applied in such a simulator. At last, the protocol of [2], [9], [10] were tested by network topologies of the ring, square-grid, and random respectively while the HQRP is tested on random, star, and ring topologies and was in the same performance efficiency.

Table 2. Comparison between HQRP with the most relevant studies

| References | Routing parameters | GUI simulation | Topology |
|---|---|---|---|
| [9] | Link entanglement rate<br>Ring number per distance | - | Ring topology |
| [10] | Knowledge of network topology<br>Location of end-use<br>Current link state knowledge | - | square-grid topology |
| [21] | Use graph state for routing<br>Within regional networks | - | - |
| [22] | Use graph state for routing | - | - |
| [2] | Link entanglement rate | - | Random topology |
| HQRP | Hybrid of:<br>− Entanglement rate hup count | Impelemet the protocol in Gui Q.Net.Sim. | – Random<br>– Star<br>– Ring |

## 4. CONCLUSION

This paper presents a new study about routing in quantum networks, and in particular the quantum internet. Where an algorithm was presented for making a routing decision for the best path in the quantum network, and as a result, this study was able to find a mathematical model that can determine the optimal path among several paths within the quantum network according to a hybrid metric of both classical and quantum network metrics such as hop count and the probability for long-distance quantum entanglement respectively which is described in detail in section 3.1. We conclude from this study, that the quantum system is based on the principle of entanglement probability, so the best path in a quantum network depends on the higher probability of end-to-end with the minimum count of hops along the path. In addition, the success rate of quantum entanglement does not depend on the number of nodes present in the path. Rather, it depends on the distance between any two nodes in the network. Finally, the proposed protocol is not affected by the type of network topology, It can be applied to any network topology.

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