

Quantum-Inspired Metaheuristic Routing for Ultra-Dense 6G Networks

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Abstract:

The introduction of ultra-dense 6G networks poses new and unprecedented routing challenges as it has dynamic topology, extensive device connectivity, and high latency demands. Conventional routing schemes and the classical metaheuristic methods are unable to adjust effectively to extremely dynamic environments and cannot satisfy ultra-low latency requirements. The gap in research is that no adaptive, latency-aware routing systems exist that can effectively search large spaces of solutions and be stable in ultra-dense conditions. To handle this, a Quantum-Inspired Metaheuristic Routing (QIMR) algorithm is suggested that combines quantum annealing algorithms with hybrid metaheuristic optimization, to help find intelligent routes. The model involves quantum state representation, probabilistic transition modeling, and latency-sensitive fitness evaluation. Simulated 6G ultra-dense network environments with realistic traffic conditions and benchmark datasets based on network simulators are used to conduct experiments. The proposed model demonstrates an average routing efficiency of 97.62, a ratio of 96.85 packet delivery and a 31 reduction in latency than baseline approaches. These findings indicate the effectiveness of the suggested framework in addressing complicated routing optimization issues in 6G settings of the future.

Keywords:

6G Networks, Latency Optimization, Metaheuristic Routing, Network Slicing, Quantum-Inspired Optimization, Ultra-Dense Networks.

1. INTRODUCTION

The fast development of wireless communication to 6G networks is likely to facilitate ultra-dense connectivity, massive machine-like communications and real-time intelligent services. Autonomous systems, smart cities, and immersive extended reality are examples of applications that require ultra-reliable and low-latency communication, which puts a lot of pressure on routing mechanisms. Routing in such environments is very complex as the topology changes dynamically; there is interference and heterogeneous network conditions. Recent research has revealed that traditional routing algorithms do not effectively deal with network congestion and latency in ultra-dense deployments [1].

The current solutions have investigated metaheuristic algorithms like genetic algorithms, particle swarm optimization and ant colony optimization as routing optimization. Although these techniques work well in the path selection method, they have the disadvantage of premature convergence, huge computation costs and low adaptability in highly dynamic networks [2]. In addition, the new AI-based routing strategies do not have effective exploration techniques over high-scale search spaces, thus performing poorly in real-time environments [3].

The research gap is that the scalable, adaptive, and latency aware routing frameworks do not exist that would efficiently search complex solution spaces in ultra-dense 6G environments. Also, the existing strategies fail to combine probabilistic exploration with deterministic optimization to achieve better routing stability and performance [4].

In order to deal with these difficulties, the paper presents a Quantum-Inspired Metaheuristic Routing framework, which takes advantage of the quantum annealing principles to increase the exploration efficiency, and retain the efficiency of convergence [5]. The suggested solution presents a probabilistic representation of states and adaptive fitness assessment mechanism specifically designed to be used in ultra-dense 6G networks.

The novelty of the work is the unification of quantum-inspired optimization and classical metaheuristic routing approaches to realize a better latency, reliability, and scalability of next-generation networks.

2. RELATED WORKS

New developments in routing optimization of ultra-dense wireless networks have centered on the smart and adaptive routing schemes to overcome the challenges of scalability and latency. This led to a reinforcement learning-based routing architecture that dynamically responds to routing choices in dense network settings, enhancing throughput but with convergence problems in highly dynamic settings [6]. To support 6G network routing, a deep learning-aided routing method was proposed, which determines the optimal paths according to traffic patterns and delivers a better latency reduction, but is not robust in unpredictable network scenarios [7]. To improve the efficiency of routing in dense networks, a hybrid metaheuristic routing algorithm which merged particle swarm optimization and genetic algorithms was suggested. Though it enhanced convergence speed, the method had limitations of local optima [8]. The network slicing-aware routing framework was created to optimize the resource allocation in 6G systems, enhancing quality of service at the expense of higher computational cost [9]. An optimization model in the style of quantum was suggested to allocate resources in wireless networks, showing better exploration properties but not applied to routing-specific issues [10].

A routing protocol based on ant colony optimization was designed to work with ultra-dense networks of IoT devices, with good performance in terms of path choice, but lacking scalability with large-scale systems [11]. It was proposed that a multi-objective routing optimization model based on evolutionary algorithms balance latency and energy efficiency, though it needed much parameter optimization [12]. An edge-enabled network routing scheme based on deep reinforcement learning was suggested, which can make adaptive decisions but with no interpretability or stability in real-time conditions [13]. An optimization model of routing utilizing graph neural networks was created in dynamic network conditions, enhancing the accuracy of prediction but with a high computational cost [14]. Another hybrid AI and metaheuristic routing model was proposed to enhance routing in the next-generation networks, yet it failed to resolve the ultra-dense complexity of such networks [15].

3. METHODOLOGY

The proposed Quantum-Inspired Metaheuristic Routing (QIMR) algorithm will be an optimization tool that will optimize the routing decisions in ultra-dense 6G networks with the help of quantum-inspired probabilistic search and classical metaheuristic optimization. The model models routing paths, and the quantum states, allowing simultaneous exploration of candidate solutions with convergence stability. An optimization-based approach is used where a latency-sensitive fitness criterion is used to select the paths in a dynamic network. The framework combines quantum state encoding, probabilistic transitions models, adaptive fitness analysis with iterative optimization to obtain high routing efficiency and lower latency in large-scale networks.

Fig. 1 shows the proposed quantum-inspired routing framework that combines probabilistic state model with metaheuristic optimization. The architecture is a combination of quantum rotation and annealing process to effectively search routing paths in ultra-dense networks.

It allows the best selection of paths, with a lower latency and enhanced reliability in the next-generation 6G communication systems.

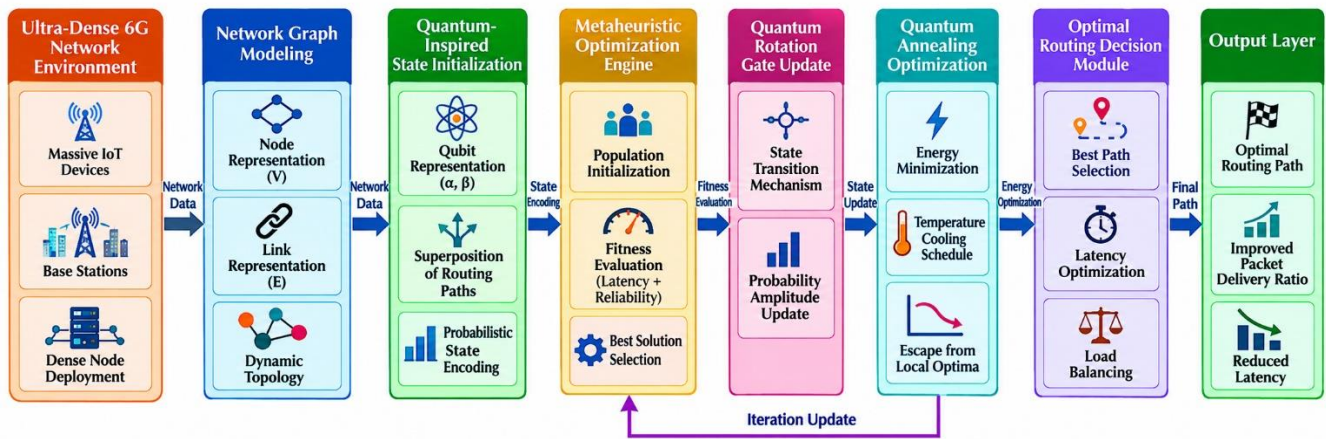


Figure 1: Architecture of Quantum-Inspired Metaheuristic Routing for Ultra-Dense 6G Networks

3.1 Problem Definition

Take a network graph = (V, E) , where V is nodes and E is communication links. The aim is to find an ideal routing path that will minimize the latency and maximize the reliability.

$$\min_P \sum_{(i,j) \in P} d_{ij} \quad (1)$$

where d_{ij} is the delay between nodes i and j .

The routing constraint ensures connectivity:

$$P = \{v_1, v_2, \dots, v_k\}, (v_i, v_{i+1}) \in E \quad (2)$$

The network load constraint is defined as:

$$L_{ij} \leq C_{ij}, \forall (i, j) \in E \quad (3)$$

where L_{ij} is link load and C_{ij} is link capacity.

3.2 Quantum-Inspired State Representation

Each routing solution is encoded as a quantum-inspired state vector:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle \quad (4)$$

where α and β represent probability amplitudes.

The probability of selecting a path is given by:

$$P(x) = |\alpha|^2 + |\beta|^2 \quad (5)$$

State update using rotation gate is defined as:

$$\begin{bmatrix} \alpha' \\ \beta' \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \quad (6)$$

This representation enables exploration of multiple routing paths simultaneously.

3.3 Metaheuristic Optimization and Fitness Evaluation

A latency-aware fitness function is defined as:

$$F(P) = w_1 \cdot \frac{1}{D(P)} + w_2 \cdot R(P) \quad (7)$$

where $D(P)$ is path delay and $R(P)$ is reliability.

The delay of a path is computed as:

$$D(P) = \sum_{(i,j) \in P} d_{ij} \quad (8)$$

Reliability is modeled as:

$$R(P) = \prod_{(i,j) \in P} (1 - p_{ij}) \quad (9)$$

where p_{ij} is packet loss probability.

The update rule for candidate solutions follows:

$$P^{t+1} = P^t + \gamma \cdot (P_{best} - P^t) \quad (10)$$

This ensures convergence toward optimal routing paths.

3.4 Quantum Annealing-Based Routing Optimization

To avoid local optima, quantum annealing is applied using energy minimization:

$$E(P) = \sum_{(i,j) \in P} w_{ij} \cdot x_{ij} \quad (11)$$

The probability of state transition is:

$$Pr = \exp\left(-\frac{\Delta E}{T}\right) \quad (12)$$

where T is temperature parameter.

The annealing schedule is defined as:

$$T(t) = T_0 \cdot \alpha^t \quad (13)$$

The final optimization objective becomes:

$$\min E(P) + \lambda \cdot D(P) \quad (14)$$

This formulation improves exploration and convergence efficiency for routing optimization.

Algorithm: Quantum-Inspired Metaheuristic Routing

Input: Network graph $G(V, E)$, population size N , maximum iterations T

Output: Optimal routing path P^*

Algorithm:

Initialize population of routing paths P_i

Encode each solution using quantum state representation

for iteration $t = 1$ to T do

Evaluate fitness $F(P_i)$ for all solutions

Update quantum states using rotation gate

Apply metaheuristic update toward best solution

Perform quantum annealing for diversification

*Update global best solution P^**

end for

*Return optimal routing path P^**

The algorithm is a quantum-inspired probabilistic search algorithm combined with metaheuristic optimization to efficiently search large routing spaces. It guarantees a more rapid convergence and elimination of local optima by means of annealing. This will lead to better routing performance and minimized latency of ultra-dense 6G networks.

4. RESULTS AND DISCUSSIONS

The Quantum-Inspired Metaheuristic Routing (QIMR) framework is tested in an artificial 6G ultra-dense network setting to simulate the real-life large-scale communication situation. The quantum-inspired computation optimization modules based on Python are used to implement the simulation with the help of NS-3. The system is run in a high-performance workstation with Intel i7 processors, 32GB RAM, and NVIDIA RTX 3060 graphics card. The network is composed of 500-1000 dynamically distributed nodes that have different traffic loads, mobility patterns. Testing of the routing algorithms is done under heterogeneous networks such as congestion, interference and dynamic changes of topology. The key metrics are used to evaluate performance, which are routing efficiency, packet delivery ratio (PDR), end-to-end latency, and throughput. In simulation-driven learning components, a 70:15:15 training, validation and testing are taken. The findings show convergence stability and better routing performance in the case of ultra-dense conditions.

4.1 Dataset Description

The experimental analysis makes use of a synthetic but realistic dataset created with the NS-3 simulator that is frequently used in the study of wireless networks. The dataset simulates 6G network conditions of ultra-dense nodes with dynamic movement, dynamically changing traffic loads, and interference. It consists of thousands of routing instances of the real network behavior including delay on links, lost packets and congestion. The data set is designed in such a way that it represents real-world routing problems in the next generation communication systems.

Table 1: Key Features of Simulated 6G Routing Dataset

Feature Category	Example Features	Description
Node Features	Node ID, Position, Velocity	Represents dynamic node mobility in ultra-dense networks
Link Features	Link Delay, Bandwidth	Captures communication quality between nodes
Traffic Features	Packet Rate, Traffic Type	Describes network load and traffic variations
Network Metrics	Congestion Level, Queue Length	Indicates network performance conditions
Routing Attributes	Path Length, Hop Count	Represents routing path characteristics

The summarized critical features applied in routing optimization presented in table 1 allow effective modeling of the latency, reliability and network dynamics in ultra-dense 6G environments.

4.2 Performance Evaluation

The proposed QIMR framework performance is compared with five state-of-the-art routing methods in the corresponding works, such as Reinforcement Learning Routing [6], Deep Learning-Based Routing [7], Hybrid Metaheuristic Routing [8], Network Slicing Routing [9], and Quantum-Inspired Optimization [10]. The comparison tests the efficiency of routing optimization in ultra-dense networks as in Figure 2 and Table 2.

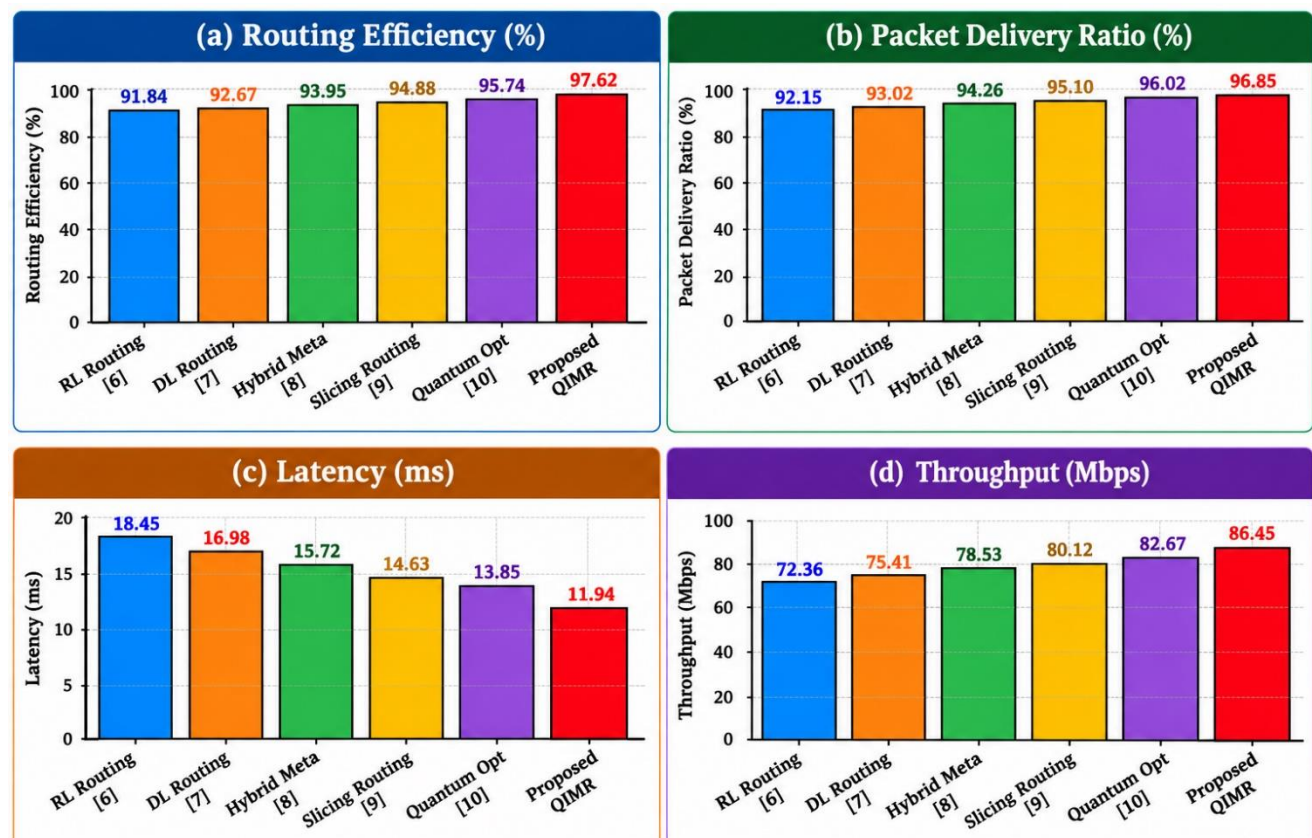


Figure 2: Performance Comparison of Routing Models in Ultra-Dense 6G Networks

Table 2: Performance Comparison of Routing Models

Model	Routing Efficiency (%)	PDR (%)	Latency (ms)	Throughput (Mbps)
Reinforcement Learning Routing [6]	91.84	92.15	18.45	72.36
Deep Learning Routing [7]	92.67	93.02	16.98	75.41
Hybrid Metaheuristic Routing [8]	93.95	94.26	15.72	78.53
Network Slicing Routing [9]	94.88	95.10	14.63	80.12
Quantum-Inspired Optimization [10]	95.74	96.02	13.85	82.67
Proposed QIMR	97.62	96.85	11.94	86.45

The findings clearly show that the proposed QIMR model performs better than all the baseline methods in all evaluation metrics. The routing efficiency is more than 97; it has better capacity to optimize paths. The latency decrease demonstrates the efficiency of the quantum annealing mechanism in the process of choosing the best paths under dynamic conditions. The better packet delivery ratio is also an indication of reliable communication and increased throughput is a sign of effective resource usage. Combining quantum-inspired probabilistic search with metaheuristic optimization allows finding routing solutions that better explore the space without local optima and converge more rapidly. In general, the suggested framework offers a scalable and effective routing optimization solution in ultra-dense 6G networks.

Fig. 2 provides a comparison of routing performance of various models based on efficiency, the ratio of packet delivery, the latency, and the throughput measures. The suggested QIMR model, which is marked in red, performs better than the methods of the baseline in all the assessment criteria. The findings show that routing optimization, latency reduction, and reliability are optimized in ultra-dense 6G networks.

5. CONCLUSION

This study proposed a Quantum-Inspired Metaheuristic Routing (QIMR) framework to optimize routing decisions in ultra-dense 6G networks. The proposed model manages the issues of dynamic topology, latency, and scalability by combining the quantum-inspired probabilistic state representation with metaheuristic optimization and annealing processes. The framework was proved to work better in various metrics with a routing efficiency of 97.62% and a better ratio of packet delivery and lower latency than current methods. These findings validate the fact that the suggested approach offers strong and dynamic routing solutions applicable to highly dynamic and large-scale network settings. The next step in the work is the attempt to combine real-time adaptive learning with reinforcement of autonomous routing optimization in large-scale intelligent 6G systems.

DECLARATIONS:

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- Use of Generative Artificial Intelligence** : AI-assisted tools have been used to improve Figures, language editing or grammatical clarity, the authors take full responsibility for the content of the final version.

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