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REVIEW ARTICLE

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INTELLIGENT ROUTING ALGORITHMS FOR 6G WIRELESS NETWORKS: A REVIEW AND ANALYSIS

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Abstract: Routing is one of the key architectural facets in the 6G networks that plays a vital role in achieving the immense data transmission rate and features that are expected from the new generation wireless communication. These developments and approaches are discussed here for the next generation of wireless communication systems known as the 6G and the key technologies include AI, ML, and Quantum-inspired computing for improved routing. It also helps the routing algorithms to be intelligent and capable of constantly adapting to the existing network conditions in order to achieve the best transmission of data, reduced latency and the best utilization of the existing resources. The survey also focuses on the use of dynamic network slicing, edge computing and improving the security measures that is an indication of how the new technologies work hand in hand to improve the routing paths of the internet. From this survey, current research trends, technological advancement, and future scope offers a clear view of how 6G networks, as the next evolution over the previous generations, will address the routing problem and foster an advanced interconnected, secure, and responsive communication framework.

Keywords: 6G networks, optimal routing, artificial intelligence, machine learning, low latency, quantum computing.

I. INTRODUCTION

The advancement of wireless communication has been phenomenal over the last few decades starting from 1G analog systems to arrive at today's 5G networks envisaged to offer blazing speed and connection. Currently, 5G is the newest generation in the development of cellular networks, promising incredible speed, dependability, and connection characteristics. It works with higher frequency bands and this enables higher data transfer rates than low-frequency bands, with latencies measured in milliseconds only [1]. Its focus on providing lightning-fast speeds and supporting as many connected devices as possible places it among the cutting-edge technologies. Routing optimization is one of the few drawbacks that can be seen with such a system in place.

Routing refers to how data packets in a network are chosen a path from a source to a destination and it is a determinative process in ensuring the data transferred between interconnecting devices is efficient and reliable [2]. An optimum Route Selection Mechanism is portrayed in figure 1. Proper routing is significant for contemporary communication media to provide uninterrupted web surfing, multimedia access, real-time services, and IoT [3]. Despite the 5G's high speed and high capacity, it sometimes fails to adapt to the optimal number of routing paths or in environments where traffic demands are fluctuating, and they never know how to direct IP flows most effectively in the rapidly evolving traffic conditions. This can lead to problems with overall network performance, resulting in the wastage of resources, inadaptability to complex systems [4], and the possibility of traffic jams within a network during high usage periods. In the future, it is expected that 6G will improve the protocol stack and have capabilities to overcome problems seen regarding the 5G technology.

6G, or the sixth generation of wireless technology is the next evolution of what has already been deemed 5G. In its essence, 6G is planned to advance the experience and performance of 5G by providing higher data level, availability, and intensity of intelligence. Intended to operate at substantially higher frequencies than 5G, 6G networks aim at providing data transfer speeds in the terabits per second spectrum that should allow almost real-time downloads, high-definition video streaming, and responsiveness that will be crucial for such applications as AR [5], VR [6], and other self-driving systems. In addition, 6G is not only about speed but also focuses on intelligence and the capability to learn about the environment and surroundings [7]. With the help of futuristic technologies, the 6G network is expected to autonomously self-complete resource management, pattern recognition of the users and control the environmental changes on its own. This intelligence has the potential to enhance industries such as healthcare, transportation, manufacturing, and entertainment to higher results, revolutionary efficiency, and productivity.

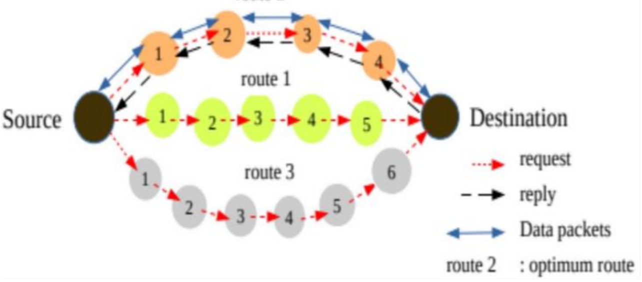

Figure 1. Optimum Route Selection Mechanism [2]

The core component in the propagation of every generation of mobile communication networks has been routing. The routing is expected to experience a revolutionary type of change as it is going to incorporate advanced technologies to enhance its function and performance. While earlier generations of networks only expectedly introduced some AI features into the networks, the 6G networks are expected to have AI and ML [8] functionalities as part of the routing protocols. This feature can change the availability of one or several routes with the help of predictive data and AI applications.

Furthermore, 6G seeks to reduce scalability and sustainability issues through potential advances like quantum computing [9]. There are the footsteps of quantum-based routing algorithms creating an impact on the conventional routing of data packets using principles such as superpositioning and quantum entanglement to perform computations at significantly high speeds and with increased efficiency. 6G aims to provide even greater levels of connection, effectiveness, and security to enable a future-oriented, advanced wireless network for tomorrow's digital environment through features such as Ultra-Reliable Low-Latency Communication (URLLC), Secure Communication (SC), and green energy. In Figure 2 illustrate the evolution of 6G.

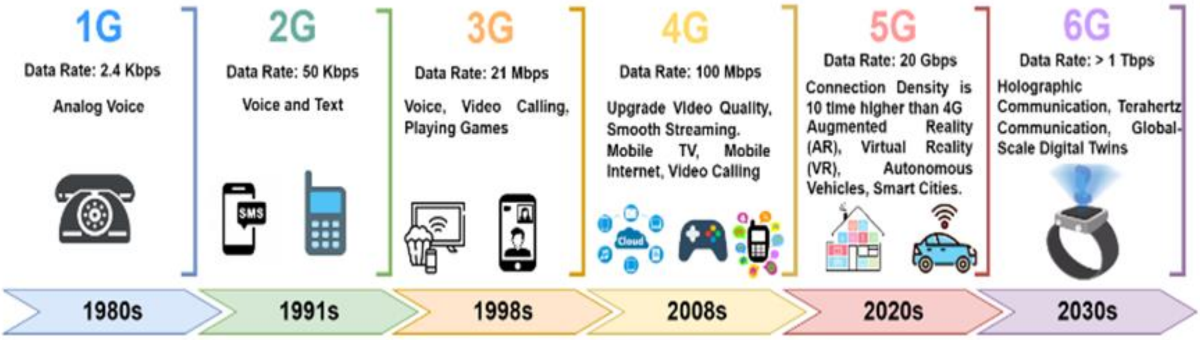

Figure 2. Evolution of 6G [9]

1.1 Challenges in Current Routing Protocols

Despite the advancements in 5G, current routing protocols face several challenges that 6G aims to overcome:

- The existing conventional routing protocols lack flexibility. They cannot handle dynamic networks as required by modern applications causing inefficiency in resource utilization and high latency at tuned traffic or node mobility. [10]
- When more devices join, extreme latency and congestion during rush hours affect the routing protocols that are challenged to maintain quality, particularly in critical applications [11].
- Current routing protocols are not easily scalable as more devices are connected and this results in creating bottlenecks and degradations in performances [12].

1.2 Faults and Failures in 6G Network Routing

Faults and failures in 6G network routing can stem from various sources, impacting different levels of the network architecture and necessitating robust fault tolerance strategies for reliable operation.

A. *Node Level*

- **Hardware Failures:** Individual nodes might encounter hardware issues like power supply failures or component malfunctions, which can disrupt how they communicate and stay connected.
- **Software Issues:** Nodes may face software glitches; such as bugs in their operating systems or application software. These issues can cause unpredictable behavior or even total operational breakdowns.
- **Energy Depletion:** Battery-operated devices can fail when their energy reserves are depleted, impacting network reliability, particularly in remote or demanding environments.

B. *Network Level*

- **Routing Protocol (RP) Errors:** Errors within routing protocols, like misconfigurations or protocol incompatibilities, can lead to inefficient routing paths, higher latency, and overall degraded network performance.
- **Data Collection (DP) Issues:** Faults in 6G networks can stem from errors in data collection processes, which compromise the accuracy and reliability of information transmitted across the network.
- **Congestion and Traffic (CT) Overload:** Heavy traffic volumes can cause congestion, resulting in delays, dropped packets, and reduced overall throughput. Effective congestion management strategies are crucial to upholding network performance.

C. *Application Level*

- **Protocol Failures:** Specific protocols used for IoT devices or real-time communications may fail due to design flaws or implementation errors. These failures can significantly impact service quality and the overall user experience.
- **Mechanism Failures:** Faults in 6G networks can occur in application-level mechanisms such as data compression, encryption, or aggregation. These issues can compromise data integrity, security, and overall network efficiency.
- **Integration Challenges:** Integrating different applications or services within the 6G network can lead to compatibility problems, data inconsistencies, or even system failures.

1.3 Fault Tolerance Strategies:

To mitigate those faults and ensure reliable operation in 6G networks, several fault tolerance techniques are essential:

- **Redundancy-Based Approaches:** Adding redundancy with duplicate routes, backup nodes, or multipath routing can strengthen fault tolerance in 6G networks, ensuring seamless operation even if nodes or paths encounter failures [13].

- **Dynamic and Adaptive Routing:** AI-driven adaptive routing algorithms optimize routing paths in real-time by adjusting to network conditions, which helps minimize the impact of faults on network performance [14,15].
- **Self-Healing Mechanisms:** AI and machine learning-powered autonomous and self-healing capabilities can detect faults and autonomously recover, minimizing downtime and ensuring continuous service availability.
- **Energy-Efficient Designs:** By developing energy-efficient protocols and algorithms within 6G networks, we can make IoT devices last longer on a single charge and reduce overall energy consumption. This not only enhances the network's sustainability but also improves its reliability.

By tackling these potential faults and implementing strong fault tolerance strategies, 6G networks can achieve the reliability, resilience, and efficiency needed to support a wide range of advanced applications in the future. Faults and Failures in 6G network routing is portrayed in figure 3 and Fault Tolerant Strategies is portrayed in figure 4.

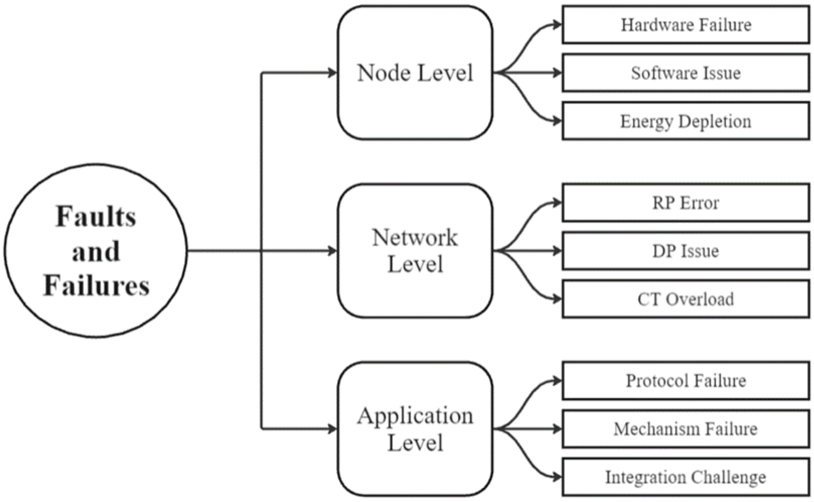

Figure 3. Faults and Failures in 6G network routing

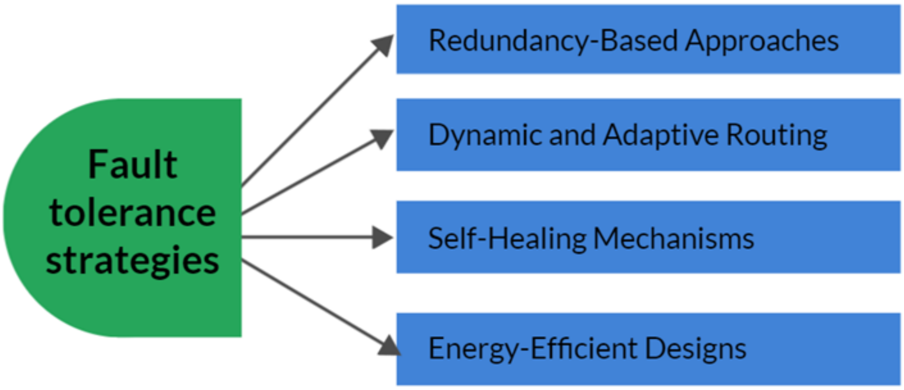

Figure 4. Fault Tolerant Strategies

II. LITERATURE SURVEY

In 6G networks, the failure of routing nodes or links can significantly impact the reliability of data transmission. To mitigate this issue, advanced routing protocols have been developed to ensure fault tolerance and enhance network reliability for efficient data transfer. This section reviews several such routing protocols in 6G networks.

Li et al. [16] enforced a Deep Reinforcement Learning Recruitment Scheme (DRLR) model to maximize the coverage ratio, minimize the DC costs, shorten the Unmanned Aerial Vehicle (UAV) path, and reduce time in 6G-based IoT networks. The Vehicular Collector Set achieved the largest data collection by employing a Genetic Algorithm. Flying distance and time of UAV were attained through Deep Reinforcement Learning (DRL) thereby eliminating combinatorial optimization problems.

Das et al. [17] devised a Hybrid Fibre Optic-Wireless (Fi-Wi) architecture to achieve ultra-low latency for communication in a 6G Wide Area Network (WAN). In this model, messages from a source node were routed to the nearest access point on the backbone network via a local wireless network. The backbone network then delivered the message with minimal latency to an access point closest to the destination node. From this access point, the message reached its intended destination through a local wireless network.

Duhayyim et al. [18] developed an Energy-Aware Data Collection with Route Planning for 6G-enabled UAV communication (EADCRP-6G) model. This model facilitated energy-efficient cluster-based data collection and optimal route planning for 6G UAV networks by using the Improved Red Deer Algorithm-based Clustering (IRDAC) technique and the Artificial Fish Swarm-based Route Planning (AFSRP) technique. The IRDAC technique was utilized for cluster formation, while the AFSRP technique was employed for route planning.

Malik et al. [19] devised a modified Ad-hoc On-Demand Distance Vector Routing (AODV) protocol to establish a routing strategy for the Cognitive Radio (CR) enabled 6G-IoT network by applying Reinforcement Learning (RL) techniques. This cross-layer architecture employed Q-Learning to predict routing decisions. Network Simulator-2 (NS-2) and Cognitive Radio Cognitive Network (CRCN) were used for the mathematical modelling of the technique.

Mesodiakaki et al. [20] developed a Robust heuristic algorithm (P-HEUR) to address user association, BH traffic routing, and the switching of BS and BH links, to achieve high energy efficiency and resilience for B5G/6G networks. The P-HEUR method consisted of three phases. Initially, the process connected user equipment (UEs) and solved Backhaul (BH) traffic routing without considering uncertainties. Then, it aimed to improve energy efficiency by deactivating base stations (BSs) and BH links while adjusting connections and routes. Finally, it accounted for demand uncertainties and deactivations, adjusting the solution to ensure constraints were met.

Tariq et al. [21] developed an AI-assisted digital-twin-enabled framework for traffic optimization in 6G networks using RL. The proposed architecture was divided into four layers. The smart application layer is meant to deliver application-dependent requirements and a digital twin layer for enabling digital representation of the physical and virtual model. The Intelligent layer combined AI and SDN/NFV/NS to achieve optimization, orchestration, and deliberation in 6G networks. Data-plane layer acted as a forwarding device for the end-users.

Urgelles et al. [22] designed the Quadratic Unconstrained Binary Optimization (QUBO) and Quantum Approximate Optimization Algorithm (QAOA) to address single and multi-objective routing optimization problems using quantum computing in 6G networks. Quantum supremacy was achieved by QAOA as it was designed to run on gate model quantum computers. For the multi-objective method, the parameterized lexicographic method was employed to find Pareto optimal point solutions.

Wang et al. [23] developed a Graph Neural Network (GNN) based optimization for UAVs within a two-tier framework in 6G IoT networks. The Relay GNN (RGNN) model was trained to select the optimal relay path using reinforcement learning techniques, while the Location GNN (LGNN) was trained to optimize UAV locations using unsupervised learning techniques. The encoder component of the RGNN-LGNN framework incorporated LSTM to extract features from the selected paths and locations.

Dong et al. [24] implemented the Deep Q-Network (DQN) based Load-Balancing Routing Algorithm (DQN-LLRA) to Low-Earth-Orbit (LEO) satellites, employing Deep Reinforcement Learning (DRL) to optimize routing decisions for 6G Space–Air–Ground Integrated Networks (SAGIN). The constellation topology of Iridium satellites involved randomly generating pairs of source and destination nodes, with routing decisions made by the source node. Once at the destination node, the route was completed, demonstrating the final routing path output.

Gururaj et al. [25] introduced the Collaborative Energy Efficient Routing Procedure (CEEPR) algorithm to enhance routing in 5G/6G networks by selecting the shortest paths. The algorithm utilized an RL algorithm for cluster grouping and employed the Multi-Objective Improved Seagull Algorithm (MOISA) for migration and attack processes. Integrating MOISA into CEEPR enabled the protocol to leverage its optimization capabilities. The CEEPR utilized the NS-2 network simulator for WSNs to assess throughput, energy consumption, network longevity, packet transmission, routing overhead, and transmission speed.

Haseeb et al. [26] devised a Multi-Hop Optimization Architecture with an efficient and trusted routing protocol for autonomous systems, employing computational intelligence. The implementation of 6G technology operated in the upper tier between network edges and sink nodes. The routing process employed optimization techniques, while the protocol ensured authentication and data privacy to secure communications.

Jadav et al. [27] devised the GRADE framework based on Blockchain and Garlic Routing (GR) to secure data exchange for Machine-Type Communication (MTC) in B5G/6G networks, applying an AI-based LSTM model. The proposed framework comprised three distinct layers. The application layer ensured authenticity, and the intelligent layer detected and classified data requests, forwarding only non-malicious requests to the 6G-based GR network. This layer pre-processed and normalized the data for re-scaling. The security layer employed the LSTM model to discard forged data requests and forward only legitimate ones, further enhanced by the IPFS protocol, which converted raw data into hashed session tags called ElGamal for easier retrieval.

Marinho et al. [28] created a 6G Ad-Hoc routing protocol named Coverage Area Increased Network (CAIN), which utilized RL techniques to expand network coverage. RL CAIN effectively employed Euclidean distance to enable communication between devices and Cluster Heads (CHs), achieving notable performance without the use of FL algorithms.

Zhang [29] devised intelligent routing algorithms to manage energy and predict capacity in 6G networks. The Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm, originally a clustering protocol for Wireless Sensor Networks (WSNs), aimed to minimize energy consumption in network nodes. Additionally, Particle Swarm Optimization (PSO) was introduced to enhance path transmission in intelligent routing, significantly boosting network efficiency.

Tilwari et al. [30] developed the Multi-Criteria Aware Integrated Decision-Making (MCAIDeM) routing protocol to unify multiple criteria into a single approach for IoT communication in 6G networks, enhancing path discovery efficiency. The protocol utilized a Modified Back Pressure (MBP) algorithm to assess network data traffic congestion levels. It integrated factors such as node residual energy, queue length, mobility, and link quality into the path selection process.

Tshakwanda et al. [31] developed a 6G network management system using a two-tiered AI/ML framework involving Speed Optimized Long Short-Term Memory (SP-LSTM) and Reinforcement Learning (RL). The SP-LSTM approach was applied for initial predictive analytics in routing, while RL dynamically managed routing applications. Q-learning, an RL technique, utilized network topology elements such as Massive MIMO, mmWave communications, network

Table I. Comparison of Different Routing protocols in 6G

Ref. No.	Protocols	Advantages	Limitations	Environment	Major performance metrics
[16]	DRLR, genetic algorithm, DRL	Does not need encoder RNN	Overfitting problem existss	---	Number of UAV collector = 2, Flying distances of UAV collectors = 500 km
[17]	Fi-Wi	Minimal queueing delay	Just a prototyped architecture	Network Simulator (NS)- 3	With 50 Mbps uplink speed and 1 Gbps downlink speed, Average TT = 46-79 µs, TT in wireless communication = 244 to 301 µs, Packets joining the queue = 0.6 to 0.9 , Latency = 380 µs
[18]	EADCRP-6G, IRDAC,AFSRP	High throughput and less delay	AFSRP has risk of early convergence	--	EC = 159mJ, Network lifetime = 4490 rounds, Throughput = 0.63 Mbps, Delay = 6.88s
[19]	NCL	Low latency and High Data Rate	Suitable for only large datasets	NS-2	PDR= 2574000 bps, Packet Loss= 20% Delay= 250 ms
[20]	P-HEUR	Very Low Execution Time	Could not cope with uncertainty	MATLAB 2019b	With 40% deviation, Γ = 5, EC = 1800000 bits/J, Execution time = 0.1s, Price of Robustness = 48% Mean Constraint Violation Probability = 0.4%, Mean unsatisfied user probability = 0.1%. All the results are taken at 6th hour of the day
[21]	Digital-twin	Enhances user experience	Suitable only for low dimension networks	--	----
[22]	QAOA, QUBO	Guaranteed performance	Not suitable for more qubits	Qiskit Runtime (IBM Cloud)	For minimizing cost, Cost=4, Throughput=4, Hops=3, For Maximizing Throughput, Cost = 7, Throughput = 10, Hops=4, For Minimising Hops, balancing cost & throughput, Cost=4,Throughput=4, Hops=2
[23]	LGNN-RGNN	Quickly adapt to new features	Heterogeneity of network is not considered	--	For $\|V_s\|$=250, $\|V_u\|$=35 PDR = 3.18 Mbps, Computation Time = 44.79s
[24]	DQN-LLRA	Low delay and reduced Queue utilization	Expensive and requires more time	Python 3.9	Path delay = 82s, Path Maximum Queue Utilization = 0.76
[25]	CEEPR, MOISA, RL	Improved Load Balancing	choosing the shortest route only canot improve QoS	NS-2	Throughput = 90% EC = 90% Network lifetime = 95% Packet transmission = 85% Routing overhead= 95%, Transmission speed = 92%
[26]	Multi-Hop Optimization	Low energy consumption	Computation overhead is high	NS-2.35	For 1000 bps, Data Delivery Ratio = 90% Nodes' overhead = 4% bps Latency = 2.8s Energy Consumption = 0.081 J Computational Cost = 7%
[27]	GRADE, GR, IPFS	Free data storage for session tags	Comprising rate is high	I2P	Data request Compromised Rate = 18%, Packet Loss Ratio = 25%, Scalability = 48ms
[28]	CAIN, RL, FL	More Battery life	Computation overhead is high	OMNeT++1 v 5.6.2 discrete event simulator	Communication delay = 2e-09, Distance = 0.32, Received message = 1.8, Overhead = 7.5 kb, Network lifetime = 3.8s
[29]	LEACH, PSO	Less energy consumption	The consumption of transmission is excessively high.	Matlab	For 350 rounds, Average energy consumption = 0.88%
[30]	MCAIDeM	Lower energy consumption	Heterogeneity of network is not considered	---	Throughput = 25 kbps Delay= 2.8 ms EC = 110 mAh
[31]	SP - LSTM	Accurate Congestion Forecasting	The functionally of multi-agent system is not clear	NetSim v13.3	Training, Prediction duration =145.8s, 21.51s. Mean Squared Error (MSE) = 1.15e-05 Training , Prediction Accuracy = 0.981, 0.9987

slicing, edge computing, SDNs, and VNFs. Open Shortest Path First (OSPF) implemented Dijkstra's shortest path algorithm to optimize data transmission paths, thereby enhancing network management. Table 1 compares all the above-studied optimal routing protocols in 6G networks in terms of their advantages, limitations and performance metrics. Energy Consumption (EC), Packet Delivery Rate (PDR), Transmission Time (TT) are the measured compared in the table.

III. CONCLUSION

In this paper, a detailed review was presented to discuss various optimal routing protocols in 6G networks. Each protocol's efficiency was summarized according to its advantages, limitations, simulation environment, and performance metrics achieved. From this analysis, it was found that the AI-Enhanced Routing Protocol outperformed other protocols due to its low routing overhead and improved decision-making capabilities. However, a significant issue with this AI-Enhanced Protocol was that packet delay remained high due to the complex computational processes involved. Additionally, it did not fully address the challenges of data transfer in highly dynamic 6G environments, impacting data delivery reliability. Future research will focus on refining the AI-Enhanced Routing Protocol to reduce packet delay and effectively increase packet delivery rates in 6G networks.

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