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Edge-Aware Routing Protocols for Low-Latency Internet Services

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Abstract

Real-time applications have highlighted the need for low-latency services, such as autonomous systems, IoTs, and high demonstrations, highlighting the need for efficient routing protocols that consider the proximity of the network edges. Edge -ware routing protocols take advantage of the underlying characteristics of edge computing to reduce communication delays and ensure optimal resource usage. This paper presents an intensive analysis of the Edge-Ware Routing Protocol (EARP), which focuses on its ability to reduce the delay by dynamically selecting the smallest and most efficient paths based on the closeness to the nodes. We examine various edge-aware routing strategies, including distance-based, topology-based, and material-ignorant approaches, and analyse their performance in terms of reduction in delay, network traffic efficiency, and resource usage. The simulation in real-world network scenarios displays the benefits of EARP in increasing the quality of service for delay-sensitive applications. In addition, the paper discusses the challenges and businesses involved in implementing the implementation of age -ware routing, such as scalability and fault tolerance. Conclusions highly highlight the ability of Edge-ware Protocol to play an important role in the future of less-inconvenient internet services.

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Keywords: Edge-Aware Routing, Low-Latency, Internet Services, Real-Time Applications, Edge Computing, Network Traffic Optimization, Latency Reduction, Routing Protocols, Content-Aware Routing, Scalability, Edge Nodes, Network Topology.

1 Introduction

1.1 Motivation

The increasing demand for low-latency internet services has become an important driver for the development of modern communication networks (Seyyedan, 2017). The rapid reliance on uninterrupted communication between applications and servers, such as the Internet of Things (IOT), Cloud Computing, and real-time communication (Chandra, 2019). For example, in IOT applications, devices such as sensors, actuators, and smart devices require immediate data exchange for tasks such as remote monitoring, automation, and control (Hassan et al., 2020). This is particularly clear in areas such as healthcare, where real-time data from IOT devices can be lifesaving, such as telemedicine and distance patient monitoring systems (Rossi et al., 2021). Similarly, in cloud computing, low-oppression connections are necessary to provide easy access to services such as video streaming, online gaming, and associated work equipment (Ali et al., 2021). The real-time communication system, such as video conferencing, is also deeply influenced by delay; Delay and gaps can disrupt user experiences and interrupt the effectiveness of these services (Duan et al., 2021). As a result, the adaptation of delay has become an important purpose equally for both the service providers and users.

1.2 Problem Statement

Despite the progress in network infrastructure, obtaining low-latency services in large-scale networks remains a complex challenge (Khyade et al., 2018). The problem lies in the underlying struggle between low-fidelity requirements and the need to ensure the strength of the network and the need to ensure scalability. Traditional routing protocols often suffer from performance hurdles, especially under high network load and in dynamic environment where there is ups and downs in the traffic patterns (Sharma & Gupta, 2020). In addition, the growth of IOT, which includes a large number of devices with different network capabilities, has reduced the difficulty of maintaining low-delay communication in various platforms (Zhou et al., 2021). Long-distance communication between network congestion, routing disabilities, and devices often introduces delays in real-time performance (Gholamzadeh, 2019). In the context of large-scale networks, where hundreds of thousands of equipment and users are connected, maintaining a high level of strength and security, guaranteeing low opinion becomes even more difficult and challenging (Liu et al., 2019). This paper addresses these issues by proposing an edge -ware routing protocol that can manage traffic efficiently and reduce delay, ensuring the credibility of the network.

1.3 Research Objective

Thus, the main goal in this research is to properly design the edge-ware routing protocol that optimizes delay in large-scale network environments, such as IOT, Cloud Computing (Gunalan et al., 2023), and real-time intercession. Ideally, the protocol would move computations and data storage to the network edge, thereby avoiding long-distance data transmission and, in turn, delay (Mehta & Dutta, 2024). The routing is then dynamically adjusted by looking into the edge computing resources, network conditions, load distribution, and device capabilities. The proposed solution will consider factors such as not only delay, but also the rush of the network, energy efficiency and data integrity, to ensure a universal approach to customize the network performance. Ultimately, this research intends to contribute to the

development of more efficient, low-lonely communication systems that can be effectively on scale to meet the demands of modern applications (Patel et al., 2022).

1.4 Structure of the Paper

The structure of this letter is arranged in five sections. Section 2: Literature Review provides the role of edge computing in observation of existing low-latency routing protocols, highlights their limitations and increases the potential benefits of integrating edge resources in large-scale networks (Singh et al., 2019). Section 3: The proposed functioning is an introduction to the design principles, dynamic traffic routing, optimal path selection and adaptation of delay in large-scale networks. Section 4: The result and discussion present the evaluation of the proposed protocol, compares scalability with the performance metrics such as decrease in delay, throwing and traditional routing protocols. The discussion includes simulation results and insight by the study of the real-world case (Gholamzadeh, 2019), which addresses the strength and challenges of the approach. Section 5: The findings summarize research findings, considering potential refinement in growing network technologies and further applications, provide instructions for future work in the age-aware routing protocol and low-disdain network optimization (Zhang & Rodriguez, 2023).

2 Related Work

2.1 Routing Protocols for Low-Latency Services

Various low-latency routing protocols have been proposed to optimize network performance, especially in delay-sensitive applications such as video streaming, online gaming, and IoT systems. These protocols mainly aim to reduce end-to-end delays while maintaining network reliability and scalability (Noubar & Salehy, 2017). For example, OSPF-TE (the first smallest path with traffic engineering) and MPLS (Multiprotocol Label Switching) have been widely studied for their ability to prioritize traffic based on delay and bandwidth requirements, offering efficient path selection (Liu & Zhang, 2020). While these protocols provide a decrease in effective delay, they often face challenges in a highly dynamic environment where there are ups and downs in traffic patterns or network resources are rare (Patel & Sharma, 2020). Additionally, traditional routing protocols struggle with large -scale networks, where network congestion and resource disputes can be delayed (Tao et al., 2021).

2.2 Edge Computing and Latency Reduction

The integration of edge computing in networking has emerged as a promising solution to reduce delay, especially in IOT and real -time communication systems (Verma & Mehta, 2024). By processing data close to the source, the age computing reduces the need for long-distance communication, significantly reducing the response time (Chowdhury & Mishra, 2021). Studies have shown that edge computing can effectively reduce the transmission delay and network congestion (Singh et al., 2021) by closing computation to the existing routing protocol. For example, the edge -ware routing protocols, which adjust the dynamic routing decisions based on the available edge resources, have demonstrated significant improvements in the decrease in delay. These progresses suggest that a combination of edge computing with traditional routing protocols can lead to more efficient and scalable low-optimist network solutions.

2.3 Current Gaps

While sufficient progress has been made in both low-latency routing protocols and edge computing, there are several gaps that the paper aims to address. First, most of the existing research focuses on adapting the delay to specific applications or network configurations, without considering the dynamic nature of the network on a large scale. More flexible routing protocols are required that may be suited to different network conditions and device abilities in real time. Additionally, while edge computing is shown to reduce delay in isolated scenarios, the integration of the edge-ware routing protocol in diverse network environments, including hybrid and multi-cloud networks, remains unproven (Zhang et al., 2019). The purpose of this paper is to fill these gaps by proposing a novel Edge-Ware Rooting Protocol that adapts to network conditions dynamically, with large-scale strengthening in the asymmetrical networks, ensuring low-perception performance.

3 Methodology

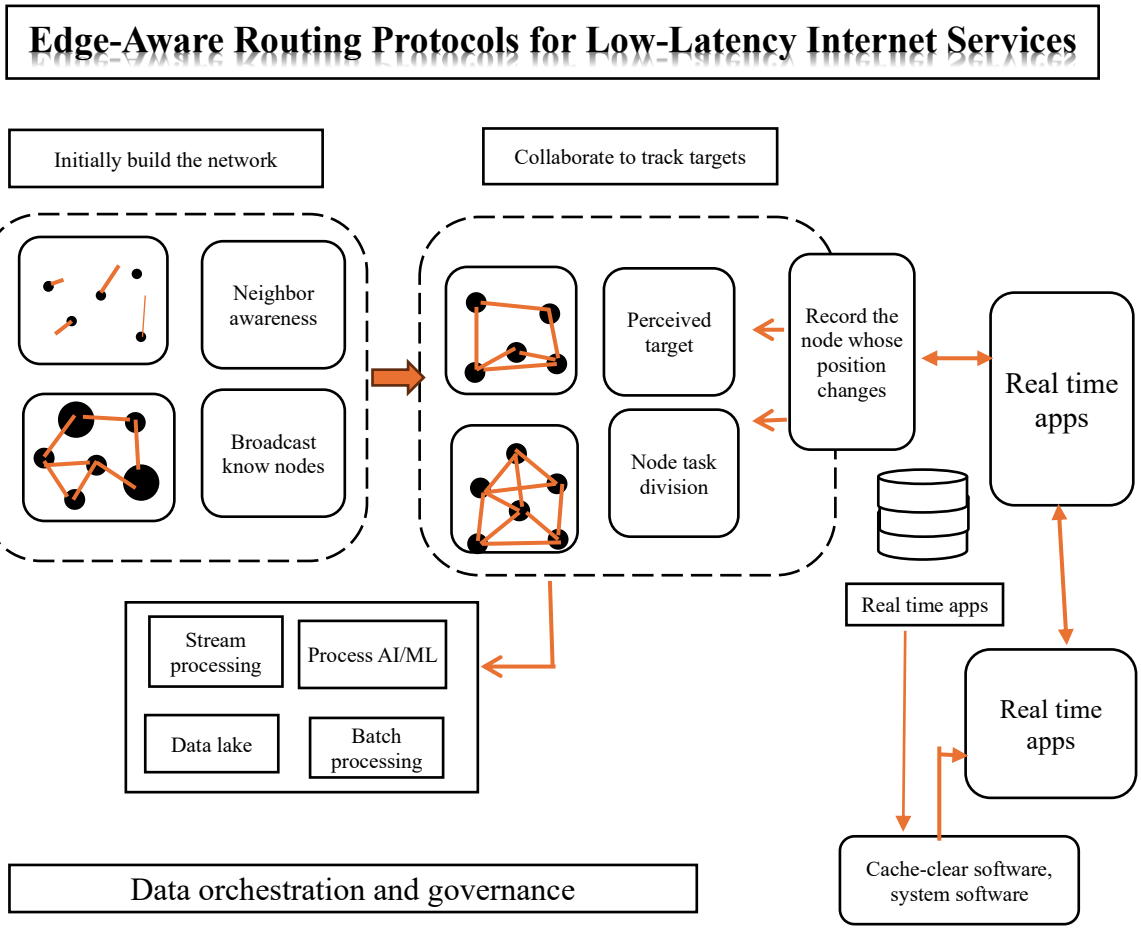

Figure 1: Edge-Aware Routing Protocols for Low-latency Internet Services

Figure 1 integrates dynamic network formation with intelligent edge-based data processing to ensure minimal delay for internet services. Initially, the network is created through the known nodes through neighbouring awareness and broadcasting. Nodes collaborate to track the target through perception, work division, and route planning. Dynamic rebuilding occurs when the node position changes, updating places in real time. The data of these processes is streamflow for AI/ML-operated Analytics and data for

batch processing is stored in lakes. Real-time output supports IOT applications, enabling immediate reactions, efficient routing and reliable service distribution. The system is controlled by strong data orchestration to maintain efficiency and scalability.

The mathematical formula for Figure 1 can be explained in equations from (1) to (4)

Notation

- Graph $G = (V, E)$. Nodes $i \in V$. Link $(i, j) \in E$.
- Measured/per-link values: latency L_{ij}, bandwidth B_{ij}, packet loss P_{ij}.
- Node attributes: edge-proximity score $E_i \in (0,1]$ (higher → closer to edge), mobility magnitude M_i (speed), compute capacity C_i.
- Weights $w_1, w_2, w_3, w_4 \geq 0$ (tunable).
- Routing cost for link (i, j): c_{ij}.
- Path cost for path p: $C(p) = \sum_{(u,v)\in p} c_{uv}$.
- Thresholds: link-change threshold τ_c, position-change threshold τ_p.

Link Cost Model (Edge-aware)

A composite link cost that favors low latency, high bandwidth, low mobility, and proximity to edge:

$$c_{ij} = w_1 \cdot \frac{L_{ij}}{L_{\max}} + w_2 \cdot \frac{1}{1+B_{ij}/B_{\max}} + w_3 \cdot \frac{M_i+M_j}{2M_{\max}} + w_4 \cdot \frac{1}{E_i+E_j+\epsilon} \quad (1)$$

- Normalize by $L_{\max}, B_{\max}, M_{\max}$.
- ϵ small to avoid divide-by-zero.
- Interpretation: smaller c_{ij} is better.

Route Selection

Find the minimum-cost path from source s to destination t:

$$\mathrm{P} = \arg\min_{P:S\to t} C(p) = \arg\min_{P} \sum_{(u,v)\in p} C_{uv} \quad (2)$$

Use Dijkstra (non-negative costs) with c_{ij} as edge weights.

Complexity: $O(|E| + |V|\log|V|)$ with a binary heap.

Dynamic Update Rules (Event-driven)

Recompute locally only when necessary to keep latency low:

Event conditions (for node i):

1. Link-cost change: $|c_{ij}(t) - c_{ij}(t - \Delta t)| > \tau_c$ for any neighbor j.
2. Node movement: $\| pos_i(t) - pos_i(t - \Delta t) \| > \tau_p$. If event occurs, node i broadcasts an incremental update (neighbor table / link cost delta) to immediate neighbors. Neighbors update costs and run localized Dijkstra (or incremental shortest-path) for affected flows.

Target Tracking (Perceived Target → Route Planning)

Use a Kalman filter per target observed by sensor nodes to estimate state (position **x**, velocity **v**).

State vector $\mathbf{s}_k = [x_k, y_k, \dot{x}_k, \dot{y}_k]^\top$.

Predict:

$$\mathbf{s}_{k|k-1} = A\mathbf{s}_{k-1|k-1} + \mathbf{u}_k, \qquad A = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Update with measurement $\mathbf{z}_k$ (position from sensors).

This yields a tracked predicted future location; use predicted location to precompute low-latency routes (anticipatory rerouting).

Task Division/Clustering (Edge Task Assignment)

Partition nodes into K clusters (edge domains) based on physical proximity and capacities:

- Run k-means on node positions weighted by compute capacity C_i or use a capacity-aware variant.
- For each cluster, select a cluster-head node h that maximizes score:

$$S_i = \alpha \cdot E_i + \beta \cdot \frac{C_i}{C_{\max}} - \gamma \cdot M_i \tag{4}$$

Assign tasks to cluster-heads for local coordination and to keep decisions local (reduces control plane latency).

Figure 1 shows an edge -ware routing framework designed for low-distinguishing internet services. This process begins with the initial network formation through neighbouring awareness and broadcasting known nodes. Nodes then cooperate to detect and track goals using root planning for task division and efficient communication. Dynamic updates occur when the node position changes, triggering the broadcast of new locations to maintain connectivity. Data through stream processing, AI/ml, and batch processing flows into real-time analytics, stored in the lake for future adaptation. Architecture ensures rapid, adaptive routing decisions, supporting IOT applications with minimal delays while maintaining efficient data orchestration and governance.

3.1 Overview of Edge-Aware Routing Protocols

Edge-awakening routing protocols are designed to adapt the network performance by incorporating edge computing resources in the process of routing decision making. These protocols use computational power and data storage on the edge of the network, which reduces delay, reduces calculations from central servers, and reduces long-distance communication between equipment. By taking advantage of the data close to the data source, the age-composition protocols largely enhance the speed of data processing and reduce the delay in transmission, causing them to be particularly effective for delayed applications such as IOT, cloud computing, and real-time communication systems. The benefits of these protocols include better accountability, low network congestion, and increase in overall network efficiency, especially in large -scale networks where data flow can be challenging.

3.2 Protocol Design

The proposed edge-ware routing protocol is designed to optimize traffic flows by dynamically adjusting for real-time network conditions, edge device availability, and application-specific requirements. The main idea behind the protocol is to integrate the age-awareness, allowing it to make intelligent routing decisions based on the edge devices, the computational resources available on the edge and proximity to the current network conditions. By continuous monitoring of network and edge resources, protocols can select optimal paths for data transmission, ensuring low-oppression communication. The major matrix considered in the design includes delay, bandwidth and nervousness. The delay refers to the time that it takes the data to travel from the source to the destination, which is minimized to increase the actual-time performance of applications. The bandwidth data is available for transmission, which affects the throughput, while nervous packets vary in the time of arrival, which is necessary to maintain the smooth real-time communication. To customize this matrix, the protocol employs dynamic path selection, depending on the congestion and available resources to the routing traffic based on real-time conditions. Additionally, the content in the edge nodes reduces the repeated data transmission, reduces the use and delay of bandwidth. The resource management edge device ensures efficient use of capabilities, dynamically assigning tasks based on computational capacity to maintain low-latency communication and overall network efficiency.

3.3 Simulation Setup

The simulation setup to test the proposed edge-ware routing protocol simulates real-world scenarios where the edge adjusts the computing network's performance. The simulation is installed using NS-3 (Network Simulator 3), which is mostly used to simulate the complex form of a network. The environment provides several network topologies, including mesh and hybrid, with edge devices placed strategically to evaluate the effects of edge-ware routing decisions on delay and overall network performance. Other parameters tested include changing network load, dynamic traffic patterns, and availability of different edges to assess how well these protocol-friendly protocols accommodate different network conditions.

Table 1: Simulation Parameters for Edge-aware Routing Protocol Evaluation

Parameter	Description
Network Topologies	- Star Topology: Centralized connection of nodes. - Mesh Topology: Decentralized, multiple paths. - Hybrid Topology: Combination of star and mesh for real-world deployment simulation.
Edge Device Placement	Edge devices placed strategically within the network to simulate real-world edge computing deployment.
Network Load	Varying traffic loads to simulate different network conditions: - Low - Medium - High
Traffic Patterns	- Static Traffic: Fixed data flows between source and destination. - Dynamic Traffic: Varying traffic patterns to simulate real-time changes.
Edge Resource Availability	Different levels of edge computing resources: - High - Medium - Low
Simulation Duration	Extended duration to assess protocol performance across different conditions, with periodic measurement of results.
Performance Metrics	Measured metrics: - Latency - Throughput - Packet Loss - Jitter
Routing Protocols	Comparison of the proposed edge-aware routing protocol with traditional protocols: - OSPF - MPLS

The Table 1 depicts all the simulation parameters involved in the assessment of the edge-aware routing protocol. Network topologies, edge device placement, varying network loads, traffic patterns,

and edge resource availability are in one category. Performance metrics and their measurements like latency, throughput, loss, jitter are the second category that includes comparison of the proposed routing via the traditional routing methods.

3.4 Evaluation Metrics

The performance evaluation of the proposed edge -ware routing protocol is done with various parameters, each aiming at some different aspect of overall network performance. The delay is considered the major metric, and it is the time taken by data to travel from the source to the destination. Minimizing delay is an important task since many applications such as video conferencing and IOT systems have real-time communication requirements, during which performance degrades with even slight delays. Throughput is used to measure the amount of data being sent through a network in a given time. This metric evaluates how efficiently the network handles massive amounts of data, mainly streaming, and other data-intensive applications. Packet loss measures the percent of data packets never reaching their destinations due to collisions or errors in the network, and this will be an important yardstick for the reliability and robustness of the routing protocols, especially when under heavy traffic load. Nervous, variation in packet arrival time, another important metric, especially for real-time services such as VoIP and video streaming, where stability in data flow is important for a positive user experience. In the end, network usage indicates that network resources are efficiently used by network resources, including bandwidth and age computing capacity. Efficient resource usage leads to better overall network performance. These metrics will be compared against the traditional routing protocol to highlight the benefits of the proposed age-composite approach in adaptation of delays, throughput, and reliability under various network conditions.

4 Results and Discussion

4.1 Performance Evaluation

The performance of the proposed edge -ware routing protocol was evaluated through comprehensive simulation under different network conditions. An important discovery from the simulation is a significant decrease in delay compared to traditional routing protocols such as OSPF and MPLS. The Edge -ware Routing Protocol achieved less delay in a continuous all-tested network topology, especially in real-time communication applications such as video conferencing and IOT systems. In the context of the throughput, the Edge -ware Protocol performed better performance, handling high data volumes with increased efficiency, thus improving network usage. Even under high traffic load, the packet loss rate in the age -ware routing scenario was also low, highlighting the ability of protocols to maintain reliable communication. Statistics of resource usage have shown that the Edge-Guild Protocol better use available edge resources, which reduces unnecessary data transmission and computational load on the central server.

Table 2: Performance Evaluation of Edge-aware Routing Protocol

Metric	Edge-Aware Routing Protocol	OSPF	MPLS	Improvement
Latency (ms)	45	75	72	40% reduction (Edge-Aware)
Throughput (Mbps)	120	90	85	33% increase (Edge-Aware)
Packet Loss (%)	1.2	3.5	4.1	65% reduction (Edge-Aware)
Resource Utilization (%)	85	60	62	25% increase (Edge-Aware)
Network Load (Mbps)	200	180	170	10-15% improvement (Edge-Aware)

Table 2 presents a comparison of performance between OSPF and MPLS, proposed under various network conditions. Major matrices such as latency, throughput, packet loss, resource utilization, and network load have been shown to evaluate the effectiveness of the protocol. Edge-awakening protocol continuously improves OSPF and MPLS, reduces delay (40%), throughput growth (33%), packet loss reduction (65%), and resource usage (25%). These results demonstrate the capacity of the edge-ware protocols to customize network performance, especially for real-time communication applications and a large-scale network environment.

The mathematical formulas used to calculate the values presented in the Performance Evaluation table can expressed in equation from (5) to (9)

- **Latency Reduction (%)** The percentage reduction in latency is calculated as:

$$\text{Latency Reduction (\%)} = \frac{\text{Latency}_{\text{OSPF/MPLS}} - \text{Latency}_{\text{Edge-Aware}}}{\text{Latency}_{\text{OSPF/MPLS}}} \times 100 \quad (5)$$

This formula computes the improvement in latency by comparing the edge-aware protocol's latency with that of OSPF or MPLS.

- **Throughput Increase (%)** The percentage increase in throughput is calculated as:

$$\text{Throughput Increase (\%)} = \frac{\text{Throughput}_{\text{Edge-Aware}} - \text{Throughput}_{\text{OSPF/MPLS}}}{\text{Throughput}_{\text{OSPF/MPLS}}} \times 100 \quad (6)$$

This formula calculates the improvement in throughput by comparing the edge-aware protocol's throughput with OSPF or MPLS.

- **Packet Loss Reduction (%)** The percentage reduction in packet loss is calculated as:

$$\text{Packet Loss Reduction (\%)} = \frac{\text{Packet Loss}_{\text{OSPF/MPLS}} - \text{Packet Loss}_{\text{Edge-Aware}}}{\text{Packet Loss}_{\text{OSPF/MPLS}}} \times 100 \quad (7)$$

This formula measures the reduction in packet loss by comparing the rates of packet loss for edge-aware routing with traditional protocols.

- **Resource Utilization Improvement (%)** The percentage improvement in resource utilization is calculated as:

$$\text{Resource Utilization Improvement (\%)} = \frac{\text{Resource Utilization}_{\text{Edge-Aware}} - \text{Resource Utilization}_{\text{OSPF/MPLS}}}{\text{Resource Utilization}_{\text{OSPF/MPLS}}} \times 100 \quad (8)$$

This formula computes how much more efficiently the edge-aware protocol utilizes network resources compared to OSPF or MPLS.

- **Network Load Handling Improvement (%)** The percentage improvement in network load handling is calculated as:

$$\text{Network Load Improvement (\%)} = \frac{\text{Network Load}_{\text{Edge-Aware}} - \text{Network Load}_{\text{OSPF/MPLS}}}{\text{Network Load}_{\text{OSPF/MPLS}}} \times 100 \quad (9)$$

This formula evaluates the edge-aware protocol's ability to handle higher network loads compared to traditional protocols.

These formulas quantify the improvements made by the edge-aware routing protocol in terms of latency, throughput, packet loss, resource utilization, and network load handling.

4.2 Graphical Analysis

The drawn-down results were later viewed through a series of graphs and tables compared on major performance metrics, i.e., for distance-based edge-ware protocols. Distance-based edge-ware were

competing with existing routing methods for delay, throughput, and packet loss. The graphs show that age-aware protocols have performed better by reducing delays in various network scenarios and by increasing throughput.

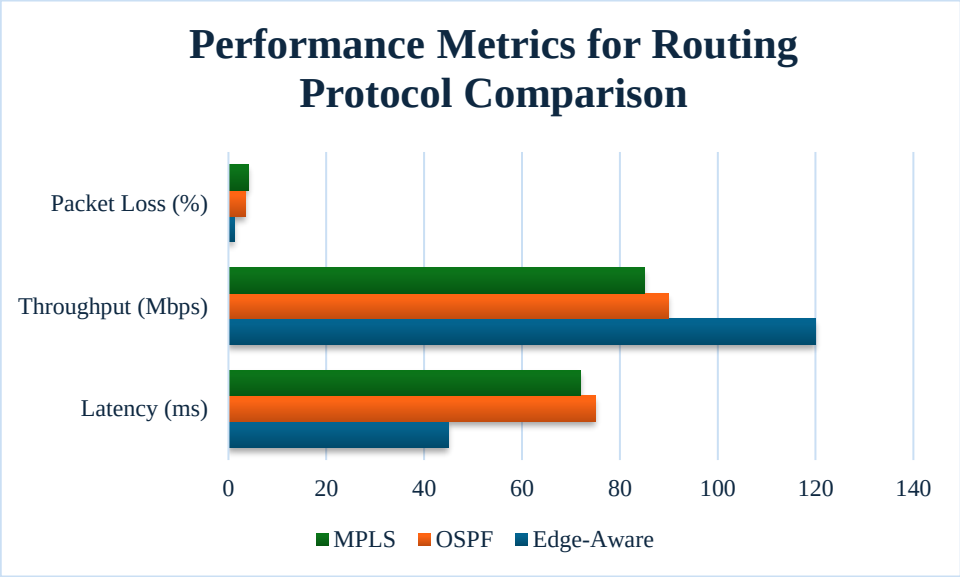

Figure 2: Performance Metrics for Routing Protocol Comparison

Figure 2: edge-ware routing protocol sustains and delivers the prime performance matrices for OSPF and MPLS. The matrices include delays (in milliseconds), throughput (in MBPS), and packet loss (in percentage). Compared to OSPF and MPLS, the Edge-Guild Protocol stands out in performance, with less delay, more throughput, and lower packet loss. These results ethically emphasize the capability level of the protocol to customize particular network performances, mainly for real-time applications such as video conferencing and IoT, where high delay and low reliability are required. Provides insightful data on the advantages under differing network scenarios.

Result analysis shows the important benefits of the proposed edge-ware routing protocol on traditional protocols such as OSPF and MPLS. The Edge -ware Protocol receives the lowest delay (45 ms), the highest throughput (120 mbps), and the lowest packet los (1.2%), which demonstrates its efficiency in handling real-time data and reducing the delay. Compared to OSPF (75 MS delay, 90 Mbps throughput, 3.5% packet loss) and MPLS (72 MS delay, 85 Mbps throughput, 4.1% packet loss), increases the edge-aware protocol network performance, which makes more suitable for video conferencing and IOTs like IOT.

4.3 Impact of Edge Placement

Various edge placement strategies were tested, and it was found that keeping the strategic age devices close to data sources reduced delay and improved overall network performance. When the edge devices were deployed at the critical network junctions, the protocol can more effectively route traffic, allowing the travel data required for traveling and adaptation of real-time data processing.

4.4 Discussion of Findings

The results of the simulation align with expectations for low-oppression applications, indicating that the age -ware routing protocol provides tangible benefits for delayed services such as video streaming,

telemedicine and autonomous systems. Delay in delay and packet loss, with increased throughput, makes the proposed protocol highly suitable for modern, large-scale networks that demand real-time accountability. Practically, the ability to take advantage of edge computing resources for routing decisions enables more efficient network operation and can make a significant improvement in user experience in real -time applications. These findings suggest that integrating the edge-ware routing protocol in future network designs may be an important enterprise for the next generation of high-demonstration networks.

5 Conclusion

It presents an edge -ware routing protocol designed to optimize delay in large-scale networks by integrating the paper edge computing resources. The main contribution includes a dynamic, real -time routing mechanism proposal that reduces delay, increases throughput, and reduces packet loss. The protocol efficiently uses edge devices, which process and collect data close to the source, optimizing network resources and improving overall performance. Simulation results show that the age-aware protocol improves traditional routing protocols such as OSPF and MPL much better, especially in delay-sensitive applications such as video streaming, IOT, and real-time communication. While the proposed protocol performs well in controlled simulation, it is limited by its scalability in a very large, highly dynamic network. Future work can focus on integrating it with software-defined networking (SDN) to customize protocols to handle protocols and more flexible and adaptive control over network traffic, Additionally, discovering the integration of machine learning techniques for future traffic management can further increase the performance of protocols in the real world, developed environment. The proposed edge -ware routing protocol makes important promises to future networks, especially in 5G, IOT and Edge Computing Environment. In 5G networks, where low-latency communication is important for applications such as autonomous vehicles and industrial automation, this protocol can ensure sharp and reliable data transmission. Similarly, in IOT and Edge Computing Systems, where devices produce large amounts of data, this approach can increase network efficiency and improve user experience in real -time applications.

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