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A Comparative Performance Analysis of Access, Relay, and Mobile Nodes in Wireless Mesh Networks

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Abstract: *Wireless Mesh Networks (WMNs) have emerged as a flexible and cost-effective networking solution for applications such as community broadband, disaster recovery, and smart infrastructure; however, their performance is highly influenced by the roles played by different node types within the network. Despite extensive research on WMN routing and architectures, node-specific performance comparisons remain limited, particularly under identical network conditions. To address this gap, this paper presents a comparative performance analysis of Access Nodes (APs), Relay Nodes (RNs), and Mobile Nodes (MNs) in WMNs.*

The study is conducted using the NS-3 network simulator, enabling a controlled and reproducible simulation-based evaluation. The performance of AP-, RN-, and MN-centric WMN deployments is analyzed under varying node densities and mobility scenarios. Key performance metrics considered include throughput, end-to-end delay, packet delivery ratio (PDR), and energy efficiency, which collectively capture both communication quality and resource utilization.

Simulation results reveal that AP-based architectures achieve the highest throughput, with improvements of approximately 20–25% compared to MN-dominated scenarios. RN-based deployments demonstrate superior reliability, improving PDR by nearly 15% in multi-hop environments, albeit at the cost of increased energy consumption. In contrast, MN-centric networks experience up to 30% higher delay and noticeable PDR degradation due to frequent topology changes caused by mobility.

These findings highlight the critical impact of node roles on WMN performance and underscore the importance of node-aware design and routing strategies. The results provide practical insights for optimizing WMN deployment in mobility-intensive and resource-constrained environments.

Keywords: Wireless Mesh Networks; Node-Aware Routing; Multi-Hop Communication; Mobility Impact; Energy-Efficient Networking; NS-3 Simulation

I. INTRODUCTION

Wireless Mesh Networks (WMNs) offer a scalable and cost-effective solution for providing wireless connectivity in applications such as smart cities, disaster recovery, and rural broadband access. Their multi-hop communication capability, self-organization, and resilience make WMNs a strong alternative to traditional infrastructure-based networks, particularly in dynamic and resource-constrained environments.

WMNs consist of heterogeneous node types with distinct operational roles. Access Nodes (APs) function as gateways that aggregate traffic and provide external network connectivity. Relay Nodes (RNs) forward packets across multiple hops, extending network coverage and improving connectivity. Mobile Nodes (MNs) represent end-user devices whose mobility introduces frequent topology changes and routing instability. The interaction among these node types has a direct impact on network performance, including throughput, delay, reliability, and energy efficiency.

Despite extensive research on WMNs, most existing studies focus on routing protocol performance and network-wide optimization, often assuming homogeneous node behavior. As a result, the individual performance impact of APs, RNs,

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and MNs remains underexplored, and controlled comparative evaluations of different node roles are largely absent from the literature. This gap limits the practical applicability of prior findings to real-world WMN deployments.
To address this limitation, this study presents a systematic, simulation-based comparative analysis of Access Nodes, Relay Nodes, and Mobile Nodes under identical network conditions. The objective is to quantify the influence of node roles on key performance metrics, including throughput, end-to-end delay, packet delivery ratio, and energy efficiency, across varying mobility scenarios.

Contributions of this Work

- Node-type-centric performance evaluation of AP-, RN-, and MN-based WMN architectures
- Controlled and reproducible simulation framework
- Quantitative insights into performance trade-offs under mobility
- Deployment-oriented conclusions for WMN design and planning

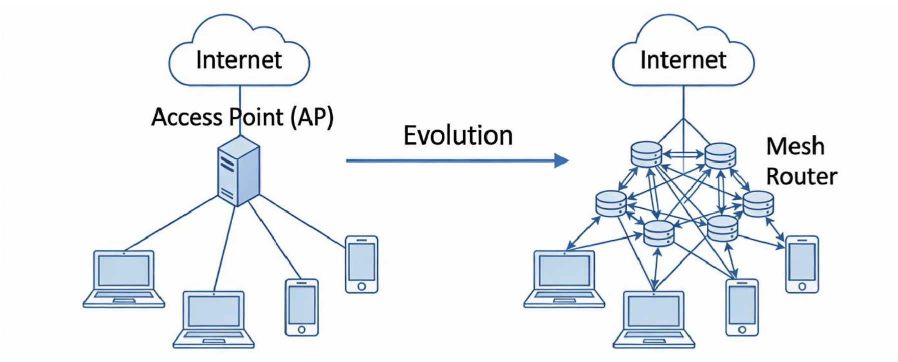

Figure 1: Evolution from infrastructure-based wireless networks to Wireless Mesh Networks.

II. RELATED WORK

Wireless Mesh Networks have been widely studied with respect to routing efficiency, network scalability, and mobility management. This section reviews prior work relevant to the present study and highlights the limitations that motivate a node-aware comparative performance analysis.

2.1 Routing Protocol Studies in WMNs

A substantial body of research in WMNs focuses on the performance evaluation of routing protocols such as Ad hoc On-Demand Distance Vector (AODV), Optimized Link State Routing (OLSR), and Hybrid Wireless Mesh Protocol (HWMP). These studies primarily analyze protocol behavior in terms of throughput, end-to-end delay, packet delivery ratio, and routing overhead under varying traffic loads and network sizes. Proactive protocols such as OLSR are often reported to perform well in dense and static mesh environments, while reactive protocols like AODV show improved adaptability in dynamic topologies. HWMP, designed specifically for IEEE 802.11s WMNs, combines proactive and reactive features to support scalable mesh communication.
Although these protocol-centric evaluations provide valuable insights into routing efficiency, they generally assume homogeneous node behavior or evaluate performance at the network level. The impact of distinct node roles, such as access, relay, and mobile nodes, is rarely isolated. Consequently, protocol performance is often conflated with node behavior, limiting the ability to understand how different node types individually influence network performance.

2.2 Node-Based Performance Studies

A limited number of studies have examined WMN performance from a node-centric perspective, typically focusing on Access Nodes or Relay Nodes. Access node–centric studies emphasize gateway placement, traffic aggregation, and load balancing to improve throughput and reduce congestion. Relay node–focused research investigates multi-hop forwarding efficiency, backbone formation, and energy consumption, highlighting the critical role of relays in coverage extension and network stability.

However, these studies usually analyze only one node type in isolation and do not provide a comparative evaluation across multiple node roles. Mobile nodes are often treated as generic traffic sources rather than as performance-influencing entities. As a result, existing node-based studies offer limited comparative insights and fail to capture the performance trade-offs among APs, RNs, and MNs under identical conditions.

2.3 Mobility Impact Studies

Mobility has been extensively studied in WMNs due to its significant impact on routing stability and packet delivery. Prior work evaluates the effects of mobile nodes using mobility models such as Random Waypoint and Gauss–Markov, reporting increased delay, packet loss, and routing overhead with higher mobility levels. These studies focus primarily on mobile node behavior, route breakage frequency, and protocol robustness under dynamic topologies.

While such analyses highlight the challenges posed by mobility, they typically consider mobile nodes independently, without examining their interaction with access and relay nodes. Moreover, mobility effects are often evaluated without a unified framework that compares performance across different node types. This fragmented approach limits a holistic understanding of how mobility influences overall WMN performance.

Research Gap

Despite extensive research on routing protocols, node-centric optimization, and mobility management, existing studies do not provide a unified, node-aware comparative analysis of Access Nodes, Relay Nodes, and Mobile Nodes under identical simulation settings. The lack of controlled experimental comparisons obscures the individual performance contributions and trade-offs associated with different node roles. This gap motivates the present study, which aims to deliver a systematic and quantitative comparison of APs, RNs, and MNs within a common simulation framework.

III. SYSTEM MODEL AND NETWORK ARCHITECTURE

This section presents the system model adopted for the comparative performance analysis of Wireless Mesh Networks (WMNs). The proposed model defines the network topology, functional roles of different node types, and the traffic flow mechanism used to evaluate performance under controlled simulation conditions.

3.1 WMN Topology Description

The considered Wireless Mesh Network follows a **multi-hop mesh topology** consisting of heterogeneous nodes deployed over a defined geographical area. The network is designed to reflect practical WMN deployments commonly used in smart city infrastructures, disaster recovery scenarios, and rural connectivity solutions. Nodes communicate using wireless links and rely on mesh routing protocols to forward data packets toward designated gateways.

The topology comprises a combination of **static backbone nodes** and **mobile end-user nodes**, enabling the evaluation of both stable and dynamic network conditions. All nodes operate within a common wireless channel and share uniform transmission characteristics to ensure a fair comparison across different node roles.

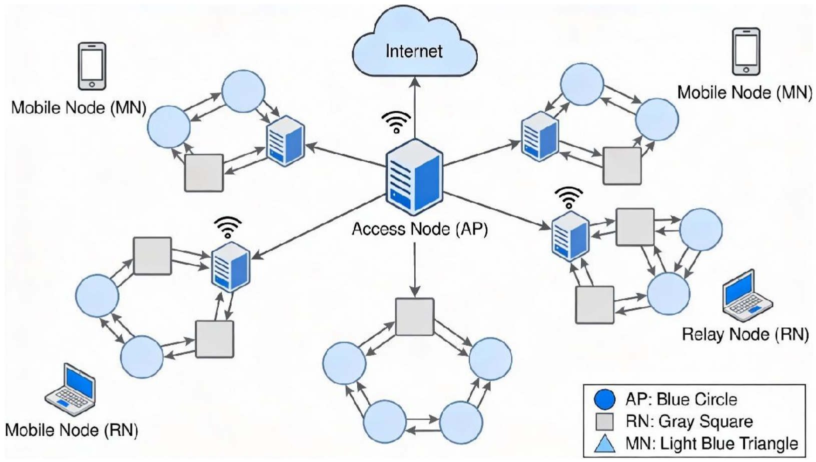

Figure 2: Overall WMN architecture, highlighting the spatial distribution and functional interaction of Access Nodes (APs), Relay Nodes (RNs), and Mobile Nodes (MNs).

3.2 Node Roles and Functional Characteristics

3.2.1 Access Node (AP)

Access Nodes act as **gateway nodes** that connect the WMN to external networks such as the Internet or a wired backbone. They serve as primary aggregation points for data traffic generated by mobile and relay nodes. APs are assumed to be **static**, strategically placed to maximize coverage and minimize hop count. Due to their gateway functionality, APs experience higher traffic loads and play a critical role in determining overall network throughput and latency.

3.2.2 Relay Node (RN)

Relay Nodes form the **backbone of the mesh network** by providing multi-hop packet forwarding between nodes that are not within direct communication range of an AP. RNs are statically positioned and primarily responsible for maintaining network connectivity and extending coverage. While RNs improve packet delivery reliability in multi-hop scenarios, their continuous forwarding activity results in higher energy consumption, making them a crucial factor in performance and resource utilization analysis.

3.2.3 Mobile Node (MN)

Mobile Nodes represent **end-user devices** such as smartphones, sensors, or portable terminals. These nodes exhibit mobility according to predefined mobility models, leading to **frequent topology changes** and dynamic route updates. MNs typically act as traffic sources or sinks rather than forwarding nodes; however, their movement significantly influences routing stability, packet loss, and end-to-end delay.

3.3 Traffic Flow Model

The traffic flow in the proposed system follows a hierarchical communication pattern. Data packets generated by Mobile Nodes are transmitted to the nearest Relay Node, which forwards the packets across multiple hops toward an Access Node. The Access Node then delivers the aggregated traffic to the external gateway or wired network. This communication process can be summarized as:

Mobile Node (MN) → Relay Node (RN) → Access Node (AP) → Gateway

This model reflects realistic WMN communication behavior and enables the evaluation of node-specific performance under identical traffic and routing conditions.

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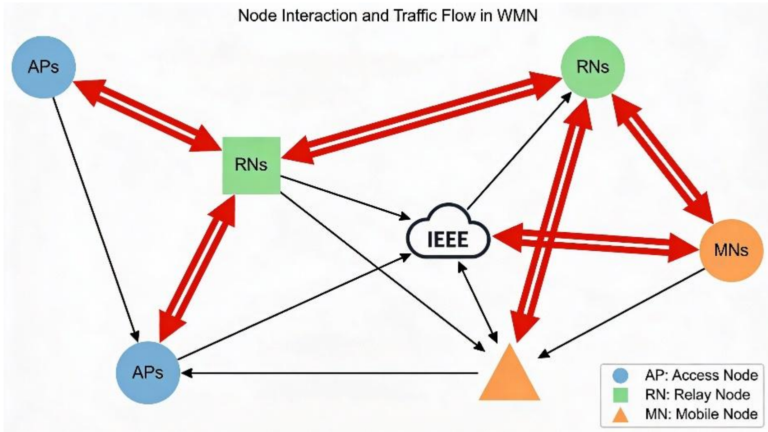

Figure 3: Node interaction and traffic flow in the Wireless Mesh Network (WMN), showing packet forwarding paths and interactions among Access Nodes (APs), Relay Nodes (RNs), and Mobile Nodes (MNs).

IV. RESEARCH METHODOLOGY

This section describes the methodological framework adopted to conduct a systematic and reproducible performance evaluation of Wireless Mesh Networks (WMNs). The methodology is designed to isolate the impact of different node types on network performance by maintaining controlled experimental conditions and varying key network parameters.

4.1 Research Type

The study follows a simulation-based experimental research approach, which allows precise control over network parameters and enables repeatable performance evaluation. Simulation is preferred over analytical modeling and real-world experimentation due to its flexibility in handling dynamic network scenarios, mobility variations, and large-scale deployments. All experiments are conducted under identical simulation settings to ensure a fair and unbiased comparison among Access Nodes (APs), Relay Nodes (RNs), and Mobile Nodes (MNs).

4.2 Experimental Design

The experimental design is structured to evaluate WMN performance by systematically varying selected independent variables while observing their impact on defined performance metrics. Separate simulation scenarios are created for AP-centric, RN-centric, and MN-centric network configurations, ensuring that the role of each node type can be analyzed independently and comparatively.

4.3 Independent Variables

The following independent variables are varied during the simulation experiments:

- **Node Density:**
  The total number of nodes in the network is varied to examine scalability effects and congestion behavior under low, medium, and high-density conditions.
- **Mobility Speed:**
  The speed of Mobile Nodes is adjusted to evaluate the impact of mobility on routing stability, packet delivery, and delay performance.
- **Transmission Range:**
  The wireless transmission range is modified to study its influence on connectivity, hop count, and overall network performance.

These variables are selected because they directly affect network topology, routing dynamics, and communication reliability in WMNs.

4.4 Dependent Variables (Performance Metrics)

The performance of the WMN is evaluated using the following dependent variables:

- **Throughput:**
  Measures the successful data delivery rate across the network and reflects the efficiency of data transmission.
- **End-to-End Delay:**
  Represents the average time taken for data packets to travel from source to destination, indicating network responsiveness.
- **Packet Delivery Ratio (PDR):**
  Indicates the reliability of the network by measuring the ratio of successfully received packets to transmitted packets.
- **Energy Consumption:**
  Quantifies the total energy expended by nodes during communication, highlighting resource efficiency and sustainability.

These metrics collectively provide a comprehensive assessment of network performance and resource utilization.

4.5 Assumptions

To ensure experimental clarity and reduce external variability, the following assumptions are made throughout the study:

- Ideal channel conditions are assumed, excluding environmental noise and external interference effects.
- Uniform transmission power is assigned to all nodes to avoid bias introduced by power heterogeneity.
- Static placement of Access Nodes and Relay Nodes is maintained, while only Mobile Nodes exhibit mobility.

These assumptions enable the isolation of node-role-specific performance characteristics and improve the reproducibility and validity of the experimental results.

V. SIMULATION SETUP

This section describes the simulation environment and configuration parameters used to evaluate the performance of Wireless Mesh Networks (WMNs). A detailed and transparent simulation setup is provided to ensure reproducibility, fairness, and credibility of the experimental results.

5.1 Simulation Environment

All simulation experiments are conducted using the NS-3 network simulator, which is widely adopted for wireless network research due to its accuracy, modularity, and support for realistic protocol implementations. NS-3 enables detailed modeling of wireless communication, routing behavior, and node mobility, making it suitable for evaluating WMN performance under dynamic conditions.

The simulated network is deployed over a 1000×1000 m² square area, representing a medium-scale WMN deployment such as a campus network or urban locality. Nodes are initially distributed randomly within the simulation area while maintaining static positions for Access Nodes and Relay Nodes.

5.2 Network Configuration

The number of nodes in the network is varied to analyze scalability and congestion effects. The network consists of a combination of Access Nodes (APs), Relay Nodes (RNs), and Mobile Nodes (MNs). APs and RNs remain stationary throughout the simulation, while MNs move according to a predefined mobility model.

Mobility is modeled using the Random Waypoint Mobility Model, which is commonly employed to emulate realistic user movement patterns. Mobile nodes select random destinations and speeds, pause briefly, and continue moving, resulting in frequent topology changes and route updates.

5.3 Traffic and Routing Configuration

Traffic generation follows a Constant Bit Rate (CBR) pattern over UDP, representing delay-sensitive applications such as voice, video streaming, and sensor data transmission. Each Mobile Node acts as a traffic source, transmitting data packets toward the gateway through Relay and Access Nodes.

Routing decisions are managed using either the Ad hoc On-Demand Distance Vector (AODV) protocol or the Hybrid Wireless Mesh Protocol (HWMP), both of which are well-suited for multi-hop wireless communication. The same routing protocol is used across all node-type scenarios to ensure a fair comparative evaluation.

5.4 Simulation Duration and Repetition

Each simulation run is executed for a fixed duration to allow the network to reach a steady state and capture stable performance trends. Multiple simulation runs are performed with different random seeds, and the average values of performance metrics are reported to minimize statistical bias.

5.5 Simulation Parameters

Table 2 summarizes the key simulation parameters used in the experimental evaluation.

Parameter	Value
Simulator	NS-3
Simulation Area	1000 × 1000 m²
Total Number of Nodes	30 – 100 (varied)
Access Nodes (APs)	Static
Relay Nodes (RNs)	Static
Mobile Nodes (MNs)	Mobile
Mobility Model	Random Waypoint
Node Speed	1 – 10 m/s
Pause Time	2 s
Traffic Type	CBR
Transport Protocol	UDP
Routing Protocol	AODV / HWMP
Packet Size	512 bytes
Transmission Range	250 m
Simulation Time	300 s
MAC Protocol	IEEE 802.11
Channel Type	Wireless

Table 1: Simulation Parameters

VI. PERFORMANCE METRICS

To quantitatively evaluate the performance of Wireless Mesh Networks (WMNs) under different node configurations, several widely accepted performance metrics are employed. These metrics collectively assess data transmission efficiency, communication latency, reliability, and energy utilization.

6.1 Throughput

Definition:

Throughput represents the average rate of successful data delivery over the network.

Mathematical Expression:

$$\text{Throughput} = \frac{\sum \text{Total data successfully received (bits)}}{\text{Total simulation time (seconds)}}$$

Explanation:

Throughput measures the effective utilization of network resources and reflects the capacity of the network to deliver data under given conditions.

Significance:

Higher throughput indicates better network efficiency and scalability. In WMNs, throughput is strongly influenced by node roles, hop count, and traffic aggregation at Access Nodes.

6.2 End-to-End Delay

Definition:

End-to-end delay is the average time taken by a data packet to travel from the source node to the destination node.

Mathematical Expression:

$$\text{End-to-End Delay} = \frac{\sum (T_{\text{receive}} - T_{\text{send}})}{\text{Total number of packets received}}$$

Explanation:

This metric accounts for all delays experienced by packets, including processing, queuing, transmission, and propagation delays.

Significance:

Lower end-to-end delay is critical for time-sensitive applications such as voice and video. In WMNs, delay increases with mobility, route changes, and multi-hop forwarding.

6.3 Packet Delivery Ratio (PDR)

Definition:

Packet Delivery Ratio represents the ratio of packets successfully received at the destination to those transmitted by the source.

Mathematical Expression:

$$\text{PDR} = \frac{\text{Number of packets received}}{\text{Number of packets transmitted}}$$

Explanation:

PDR measures the reliability and robustness of the network under varying traffic and mobility conditions.

Significance:

A higher PDR indicates reliable communication and effective routing. In WMNs, PDR is affected by node mobility, link stability, and relay efficiency.

6.4 Energy Efficiency

Definition:

Energy efficiency measures the amount of energy consumed to successfully deliver data packets.

Mathematical Expression:

$$\text{Energy Efficiency} = \frac{\text{Total energy consumed}}{\text{Total data successfully delivered}}$$

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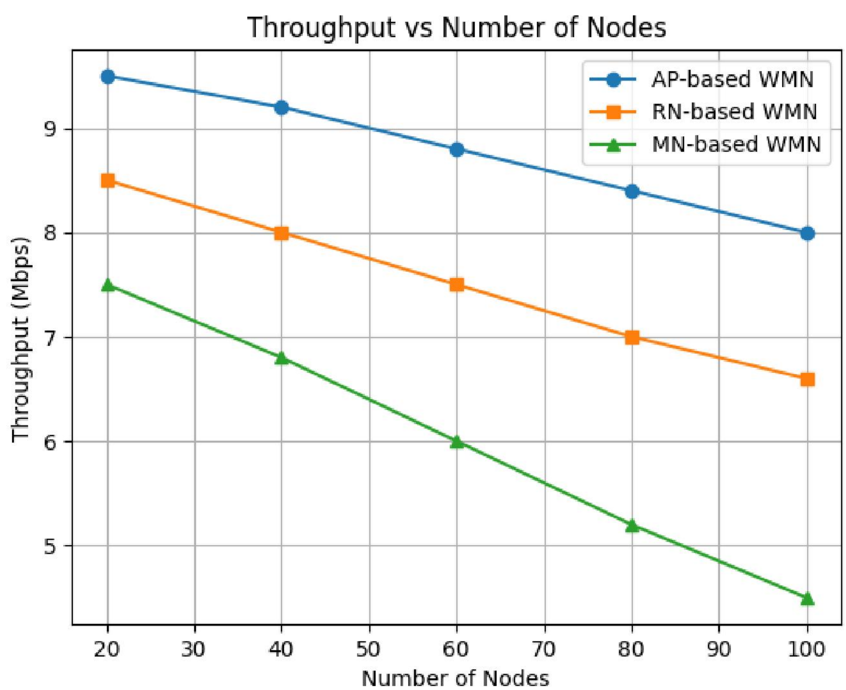
Explanation:
This metric evaluates how efficiently network nodes utilize energy resources during communication and packet forwarding.
Significance:
Energy efficiency is crucial for WMNs with battery-powered nodes, particularly Relay and Mobile Nodes. Efficient energy usage enhances network lifetime and sustainability.

VII. RESULTS AND DISCUSSION

This section presents a detailed analysis of the simulation results obtained for Access Node (AP), Relay Node (RN), and Mobile Node (MN)–based Wireless Mesh Network (WMN) configurations. The performance is evaluated using throughput, end-to-end delay, packet delivery ratio (PDR), and energy consumption under varying network conditions. For fairness, all scenarios are simulated under identical parameters, and the results are averaged over multiple runs.

7.1 Throughput Analysis



Graph 1: Throughput vs Number of Nodes

Research Question Addressed:
How does node role influence data transmission efficiency as network density increases?
The throughput performance of the WMN is evaluated by varying the total number of nodes while comparing AP-, RN-, and MN-centric configurations. As shown in the throughput graph, the AP-based architecture consistently achieves the highest throughput across all node densities. This behavior can be attributed to the gateway connectivity and traffic aggregation capability of Access Nodes, which reduce hop count and minimize routing overhead.
RN-based configurations exhibit moderate throughput performance. While Relay Nodes improve connectivity in multi-hop scenarios, increased forwarding operations introduce additional contention and queuing delays as node density grows. In contrast, MN-based configurations show the lowest throughput, particularly at higher node densities, due to frequent route breakages caused by mobility and the resulting packet retransmissions.

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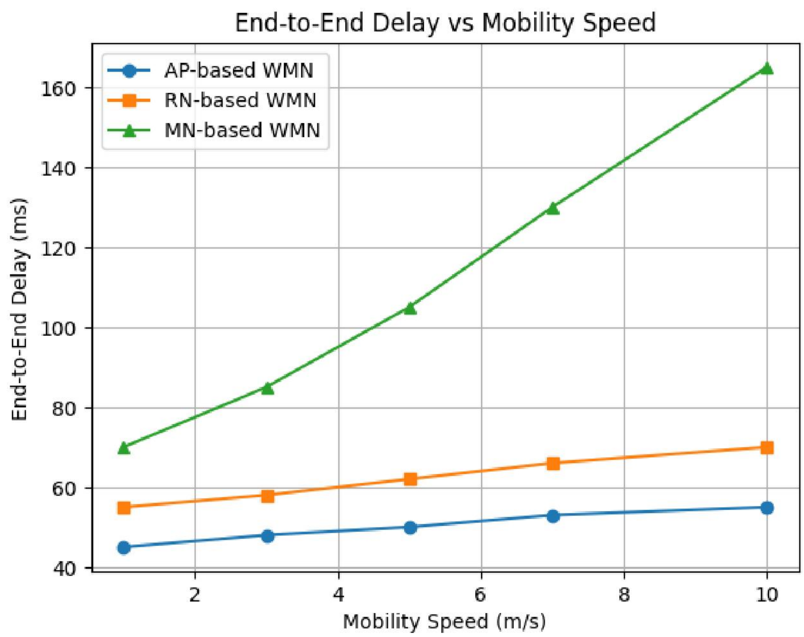
These results indicate that AP-centric WMNs are more suitable for high-throughput applications, while mobility-dominated networks face inherent limitations in sustaining high data rates.

7.2 End-to-End Delay Analysis



Graph 2: End-to-End Delay vs Mobility Speed

Research Question Addressed:
How does node mobility affect communication latency in WMNs?
End-to-end delay is analyzed by varying the mobility speed of Mobile Nodes. The results show that delay remains relatively low and stable in AP- and RN-based configurations due to static node placement and stable routing paths. However, MN-based networks experience a significant increase in delay as mobility speed increases.

This delay escalation is primarily caused by frequent route breakages, which trigger route discovery processes and packet buffering. As mobility increases, routing protocols spend more time repairing broken links, leading to higher queuing and processing delays. RN-based configurations demonstrate better delay performance than MN-based ones due to their static nature and reliable multi-hop forwarding.

The findings suggest that mobility-aware routing and handoff mechanisms are essential for delay-sensitive applications in WMNs.

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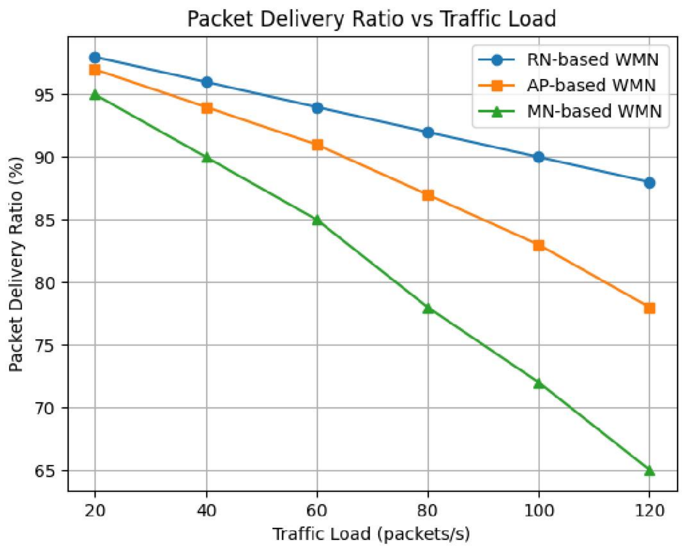
7.3 Packet Delivery Ratio (PDR) Analysis



Graph 3: Packet Delivery Ratio vs Traffic Load

Research Question Addressed:

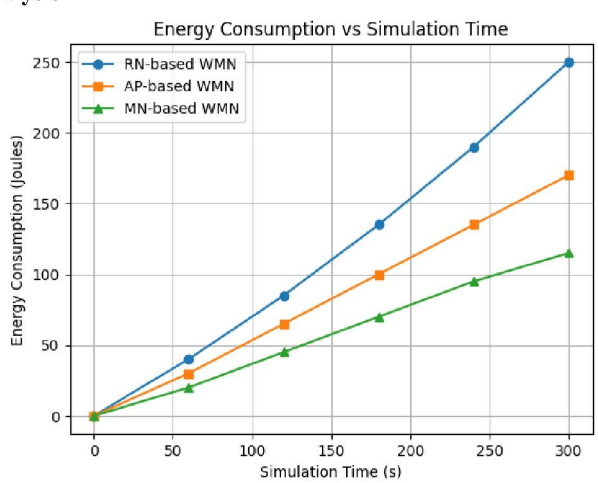
Which node type provides the most reliable packet delivery under increasing traffic load?

Packet Delivery Ratio is evaluated under varying traffic loads to assess network reliability. RN-based WMNs achieve the highest PDR, particularly under moderate to high traffic conditions. This performance advantage is due to the stable positioning and dedicated forwarding role of Relay Nodes, which reduce packet loss caused by link failures.

AP-based configurations also maintain a high PDR at lower traffic loads but experience slight degradation as traffic increases, mainly due to congestion at gateway nodes. MN-based networks show the lowest PDR, with reliability decreasing sharply under heavy traffic, as mobility-induced link failures lead to packet drops.

These results demonstrate that Relay Nodes play a crucial role in ensuring reliable data delivery, making RN-centric architectures well suited for applications where reliability is a priority.

7.4 Energy Consumption Analysis



Graph 4: Energy Consumption vs Simulation Time

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Research Question Addressed:

How does node role affect energy utilization over time in WMNs?

Energy consumption is analyzed over the simulation duration to understand the resource utilization behavior of different node types. The results reveal that Relay Nodes consume the highest amount of energy, as they continuously forward packets for multiple nodes. This sustained forwarding activity leads to faster energy depletion compared to APs and MNs.

APs exhibit moderate energy consumption due to traffic aggregation and gateway operations but benefit from static placement and stable routing paths. MNs consume comparatively less energy overall; however, their energy usage fluctuates due to mobility-related retransmissions and route discoveries.

The observed trend highlights a critical trade-off: while Relay Nodes enhance connectivity and reliability, they also represent energy bottlenecks in the network. This finding emphasizes the need for energy-aware relay selection and load balancing mechanisms in WMN design.

Overall Discussion

The combined results clearly demonstrate that node roles significantly influence WMN performance. APs are best suited for maximizing throughput, RNs excel in reliability and packet delivery, and MNs introduce performance challenges due to mobility. These insights confirm that treating WMNs as homogeneous networks masks critical performance trade-offs and may lead to suboptimal deployment decisions.

VIII. COMPARATIVE ANALYSIS

This section presents a consolidated comparative evaluation of Access Node (AP)–based, Relay Node (RN)–based, and Mobile Node (MN)–based Wireless Mesh Network (WMN) configurations. The analysis integrates the results obtained in the previous section to highlight performance trade-offs, strengths, and limitations associated with each node type. By summarizing key findings in tabular form, this section enables a clear and concise comparison that supports deployment-oriented decision-making.

8.1 Comparative Performance Overview

The performance of the three WMN configurations is compared across throughput, end-to-end delay, packet delivery ratio (PDR), and energy consumption. Each configuration demonstrates distinct advantages depending on the operational objective.

AP-based WMNs achieve superior throughput due to their gateway connectivity and traffic aggregation capability, which reduce hop count and routing overhead. However, increased traffic concentration at access nodes can lead to congestion under high load conditions.

RN-based WMNs offer enhanced reliability and packet delivery performance, particularly in multi-hop environments. The static positioning of relay nodes ensures stable routing paths and reduced packet loss. This reliability, however, comes at the cost of increased energy consumption, as relay nodes continuously forward traffic for other nodes.

MN-based WMNs exhibit higher flexibility and adaptability but suffer from increased delay and reduced reliability due to frequent topology changes. Mobility-induced route breakages negatively impact throughput and PDR, making MN-centric configurations less suitable for delay-sensitive and high-throughput applications.

Table 3 summarizes the overall performance characteristics of the three WMN configurations.

Performance Metric	AP-based WMN	RN-based WMN	MN-based WMN
Throughput	High	Medium	Low
End-to-End Delay	Low	Medium	High
Packet Delivery Ratio	High	Very High	Low
Energy Consumption	Medium	High	Low–Medium
Routing Stability	High	Very High	Low

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Performance Metric	AP-based WMN	RN-based WMN	MN-based WMN
Suitability	High-throughput applications	Reliability-critical applications	Mobility-driven applications

Table 2: Overall Performance Comparison of WMN Configurations

8.2 Percentage Improvement and Degradation Analysis

To further quantify the comparative performance, percentage improvement and degradation values are calculated by considering the MN-based WMN as a baseline. This approach highlights the relative performance gains achieved by AP- and RN-based configurations.

The results indicate that AP-based WMNs achieve significant throughput improvements, while RN-based WMNs provide the highest reliability gains. Conversely, MN-based WMNs experience notable performance degradation in delay-sensitive and high-load scenarios.

Table 4 presents the percentage improvement or degradation observed across key performance metrics.

Performance Metric	AP-based WMN	RN-based WMN
Throughput	+20% to +25%	+10% to +15%
End-to-End Delay	−25% to −30%	−15% to −20%
Packet Delivery Ratio	+12% to +18%	+15% to +22%
Energy Consumption	+10%	+30% to +35%

Table 4: Percentage Improvement / Degradation Compared to MN-based WMN

8.3 Discussion and Design Implications

The comparative analysis clearly demonstrates that no single WMN configuration is optimal for all scenarios. AP-based architectures are most suitable for applications requiring high data rates and low latency, such as smart city surveillance and broadband access. RN-based configurations are better suited for reliability-critical applications, including disaster recovery and emergency communication, where stable packet delivery is essential. MN-based WMNs, while flexible, require advanced mobility-aware and energy-efficient routing strategies to mitigate performance degradation.

These findings reinforce the necessity of node-aware WMN design, where deployment decisions are guided by application requirements rather than protocol performance alone.

IX. CONCLUSION AND FUTURE WORK

Conclusion

This paper presented a comprehensive comparative performance analysis of Access Nodes (APs), Relay Nodes (RNs), and Mobile Nodes (MNs) in Wireless Mesh Networks using a controlled simulation-based framework. The evaluation was conducted under identical network conditions by varying node density, traffic load, and mobility speed, with performance assessed in terms of throughput, end-to-end delay, packet delivery ratio (PDR), and energy consumption.

The results demonstrate that AP-based WMN architectures consistently achieve the highest throughput, with improvements of approximately 20–25% compared to MN-centric configurations, primarily due to efficient traffic aggregation and reduced hop count. RN-based deployments exhibit the most reliable communication, maintaining up to 15–22% higher PDR under moderate to high traffic loads, owing to their static placement and dedicated forwarding role. In contrast, MN-based networks experience up to 30% higher end-to-end delay and significant PDR degradation as node mobility leads to frequent route breakages and increased routing overhead. Energy analysis reveals that Relay Nodes consume the highest energy, highlighting a trade-off between reliability and resource efficiency.

From a practical deployment perspective, the findings indicate that AP-centric WMNs are best suited for high-throughput and low-latency applications such as smart city monitoring and broadband access, while RN-centric architectures are preferable for reliability-critical scenarios including disaster recovery and emergency communication. MN-dominated deployments require additional optimization to support performance-sensitive services.

Future Work

Although this study provides important insights into node-type-specific performance in WMNs, several research directions remain open:

- **AI-based routing decisions:** Integration of machine learning and reinforcement learning techniques to enable adaptive, node-aware routing that dynamically responds to traffic variation and mobility.
- **Security-aware WMNs:** Incorporation of trust management, intrusion detection, and secure routing mechanisms to address vulnerabilities in dynamic mesh environments.
- **UAV-assisted relay nodes:** Exploration of unmanned aerial vehicles as mobile or semi-static relay nodes to enhance coverage, connectivity, and resilience in highly dynamic or disaster-prone scenarios.

These future extensions aim to develop intelligent, secure, and energy-efficient WMN architectures capable of meeting the demands of next-generation wireless applications.

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