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Improvement of AODV Routing Protocol Performance in Wireless Ad Hoc Network (WANET) Using Cross Layer Approach

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Abstract: *Wireless Ad Hoc Networks (WANETs) are decentralized, self-configuring systems of mobile nodes that communicate over multi-hop wireless links without relying on fixed infrastructure. Their flexibility makes them vital in scenarios such as disaster management, defense operations, and emergency response. However, routing in WANETs is highly challenging due to node mobility, fluctuating topology, limited energy resources, and inconsistent link quality. The Ad hoc On-Demand Distance Vector (AODV) protocol is widely adopted for its on-demand route discovery, yet it suffers from excessive energy consumption, frequent route failures, and limited Quality of Service (QoS) support. This research enhances AODV through a cross-layer design approach that allows information sharing among the network, MAC, and physical layers. Three improved variants—ER-AODV (Energy-efficient and Residual Energy Aware AODV), E-AODV (Energy-aware AODV), and R-AODV (Residual Energy AODV)—are proposed to optimize routing decisions based on energy metrics, signal strength, and transmission conditions. Simulation results using NS-2 demonstrate that the cross-layer variants achieve superior throughput, reduced delay, higher packet delivery ratio, and lower energy consumption compared to standard AODV. The findings confirm that integrating cross-layer awareness significantly enhances routing efficiency, reliability, and network lifetime in dynamic and energy-constrained wireless environments.*

Keywords: Wireless Ad Hoc Networks, AODV, Cross-Layer Design, Energy Efficiency, Routing Protocol, Network Lifetime, Throughput, End-to-End Delay, Packet Delivery Ratio, Residual Energy

I. INTRODUCTION

Wireless Ad Hoc Networks (WANETs) have emerged as a crucial paradigm for dynamic and infrastructure-less communication, where each node operates as both a host and a router, enabling data forwarding through multi-hop wireless links [1], [4]. These networks are widely deployed in critical environments such as disaster recovery, military communication, sensor fields, and vehicular systems due to their rapid deployability and scalability [5], [7]. However, the inherent mobility of nodes and the absence of centralized control lead to frequent topology changes, packet collisions, and route failures, posing significant challenges for stable and energy-efficient routing [2], [8]. To address these challenges, researchers have proposed various routing protocols, among which the Ad hoc On-Demand Distance Vector (AODV) protocol has gained substantial attention due to its adaptive route discovery mechanism and low control overhead [3], [11]. Despite its robustness, AODV still suffers from route instability, high delay during route repair, and excessive energy consumption in dense or highly mobile networks [9], [13].

Energy efficiency and Quality of Service (QoS) preservation have become major optimization goals in recent ad hoc routing research [14], [16]. Energy depletion of nodes directly affects the overall network lifetime and connectivity, while QoS parameters such as throughput, end-to-end delay, and packet delivery ratio (PDR) determine the reliability of data transmission [15], [17]. Conventional AODV routing relies primarily on the network layer for decision-making

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and lacks coordination with lower layers such as the MAC and physical layers, limiting its ability to respond dynamically to fluctuating channel conditions or interference [6], [18]. To overcome these constraints, cross-layer design principles have been introduced, promoting interaction among multiple layers of the OSI model to enhance energy awareness, routing stability, and transmission reliability [19], [21].

Cross-layer optimization frameworks have been extensively explored to achieve joint adaptation of power control, link quality estimation, and congestion management [20], [22]. By enabling routing protocols to utilize information such as signal-to-noise ratio (SNR), residual energy, and node velocity from the physical and MAC layers, researchers have demonstrated significant improvements in network lifetime and throughput [23], [25]. Energy-efficient routing strategies such as Power-Aware Routing [14], Energy Conserving Routing [16], and Maximum Lifetime Routing [25] highlight the importance of balancing energy utilization across nodes to prevent early node death and network partitioning. Furthermore, adaptive topology control and cooperative link management approaches have been integrated with AODV to minimize retransmissions and delay under varying traffic conditions [29], [30].

Recent advancements in cross-layer design have emphasized dynamic coordination between routing and MAC protocols to enhance data delivery in high mobility environments [10], [18], [28]. Weiss et al. [18] proposed a cross-layer interaction model that improves routing performance through real-time MAC feedback, while Casaquite and Hwang [6] demonstrated that energy-aware cross-layer routing significantly extends the operational lifetime of wireless ad hoc networks. Similarly, Chen et al. [19] explored topology control and routing co-design to optimize multi-radio mesh networks, achieving superior link stability and reduced interference. Such studies underline that integrating cross-layer intelligence into traditional on-demand protocols like AODV can substantially improve both energy efficiency and QoS, making it suitable for modern applications involving mobile IoT devices and vehicular ad hoc networks.

Despite these developments, balancing cross-layer adaptability with protocol simplicity and scalability remains an open research challenge [26], [27]. Overly complex interactions among protocol layers can introduce additional overhead, synchronization issues, and potential violations of the OSI model's modularity. Therefore, the need arises for an Enhanced and Reliable AODV (ER-AODV) routing protocol that leverages selective cross-layer feedback to improve route stability, energy consumption, and packet delivery ratio while maintaining manageable computational complexity. The proposed ER-AODV scheme aims to optimize route selection based on dynamic metrics such as residual energy, signal strength, and link reliability, thereby achieving efficient energy utilization and sustained connectivity in highly dynamic environments [17], [20].

This study contributes to the field by developing a cross-layer enhanced version of AODV, evaluating its performance against traditional AODV and energy-aware variants (E-AODV, R-AODV) through simulations using the NS-2 platform [30]. Key performance metrics including throughput, end-to-end delay, packet delivery ratio, and energy consumption are analyzed under varying network conditions. The results demonstrate that the proposed ER-AODV achieves significant improvements in both energy efficiency and routing reliability, validating the effectiveness of cross-layer design in next-generation wireless ad hoc networks [6], [18], [25].

II. PROBLEM STATEMENT

The traditional AODV routing protocol in Wireless Ad Hoc Networks suffers from high energy consumption, frequent route failures, and limited QoS support due to its shortest-path selection and lack of cross-layer awareness. There is a need for an enhanced routing approach that integrates energy and link-quality information across network layers to improve routing efficiency, stability, and network lifetime in dynamic and resource-constrained environments.

Objectives of study:

- To analyze the limitations of the standard AODV routing protocol in terms of energy efficiency, route stability, and Quality of Service (QoS).
- To design and implement cross-layer enhanced AODV variants (ER-AODV, E-AODV, and R-AODV) that utilize information from the MAC and physical layers for improved routing decisions.

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- To evaluate the performance of the proposed protocols using simulation metrics such as throughput, end-to-end delay, packet delivery ratio, and energy consumption.
- To compare the performance of ER-AODV, E-AODV, and R-AODV with standard AODV under varying network conditions and mobility patterns.
- To recommend an optimized cross-layer routing strategy that enhances network lifetime, reliability, and overall communication efficiency in Wireless Ad Hoc Networks.

III. RELATED WORK

Several studies have addressed the challenges of energy-efficient routing, QoS provisioning, and cross-layer design in wireless ad hoc networks. Deying Li, XiaohuaJia, and Hongwei Du [1] investigated QoS topology control for non-homogenous ad hoc networks, proposing algorithms to construct network topologies that satisfy traffic and delay constraints while minimizing maximum energy utilization among nodes, thus prolonging network lifetime. Their work highlights the importance of balancing energy consumption across heterogeneous nodes, a factor often neglected in homogeneous network studies.

Cristina Comaniciu and H. Vincent Poor [2] focused on QoS provisioning in CDMA-based ad hoc networks. They proposed a joint, distributed power control and routing mechanism that ensures each active link meets a target Signal-to-Interference Ratio (SIR), thereby maximizing the perceived QoS per transmitted bit. Their approach demonstrated substantial energy efficiency improvements compared to conventional power-aware routing schemes.

Tiantong You, Chi-Hsiang Yeh, and HossamHassanein [3] introduced the DRCE MAC protocol to enhance throughput and QoS in mobile ad hoc networks. By separating small control packets from large data packets and mitigating hidden and exposed terminal problems, DRCE outperformed standard IEEE 802.11e in terms of average delay, throughput, and priority packet handling. This work underlines the role of MAC-layer innovations in improving network QoS.

The foundational Ad-hoc On-Demand Distance Vector (AODV) protocol was proposed by Charles E. Perkins and Elizabeth M. Royer [4]. AODV establishes routes on-demand, reducing control overhead and providing loop-free, quickly adaptable paths in dynamic networks. While scalable and responsive, standard AODV faces challenges in energy efficiency and route stability under high mobility. Similarly, Perkins and PravinBhagwat [5] developed the DSDV protocol, ensuring loop-free multi-hop routing through sequence numbers, although its reliance on periodic updates limits scalability in larger networks.

Energy-aware routing metrics have been explored extensively. Suresh Singh et al. [6] demonstrated that power-aware routing can reduce per-packet energy consumption by up to 70% and extend node lifetime without increasing packet delay. Deying Li et al. [7] further addressed energy-efficient broadcast routing in static networks, proposing heuristics like node-weighted Steiner trees to minimize total transmission energy. Jae-Hwan Chang and LeandrosTassiulas [8] emphasized energy-conserving routing in static sensor networks, introducing flow augmentation and redirection algorithms to maximize network lifetime while balancing energy consumption across nodes.

Energy-efficient routing for emergency and disaster recovery scenarios was studied by Gil Zussman and Adrian Segall [9], who formulated an anycast routing problem to maximize time until the first battery drain. Their iterative and polynomial algorithms provide optimal distributed solutions for networks with strict energy and bandwidth limitations.

Cross-layer design approaches have also been emphasized. Ning Yang et al. [10] showed that adaptive MAC rate selection based on PHY layer information, integrated with congestion-aware routing metrics, improves throughput, packet delivery, and end-to-end delay. Lin Chen et al. [11] introduced a Joint Topology Control and Routing protocol for multiradio multichannel mesh networks, coordinating channel selection, power control, and routing to reduce co-channel interference and enhance throughput.

Adaptive energy-based routing approaches have been proposed to extend network lifetime. LamiaRomdhani and Christian Bonnet [12] enhanced AODV by selecting routes based on node energy consumption speed, reducing total energy usage by over 20% while maintaining delivery performance. Ulag C. Kozat et al. [13] developed a cross-layer framework for energy-efficient communication with QoS provisioning, employing joint power control and scheduling to minimize transmit power while meeting end-to-end guarantees. VikasKawadia and P. R. Kumar [14] discussed

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power control protocols (COMPOW, CLUSTERPOW, MINPOW, LOADPOW) that optimize energy consumption across layers and adapt to traffic load. Finally, MirghiasaldinSeyedebrahimi and Xiao-Hong Peng [15] investigated cross-layer optimization for IEEE 802.11 WLANs, analyzing how PHY modulation, MAC retry limits, and APP-layer packet sizes jointly affect throughput and delay, demonstrating significant improvements through combined layer adaptation.

These works collectively emphasize the critical role of energy-aware routing, QoS provisioning, and cross-layer design in improving the performance and longevity of wireless ad hoc networks. The insights provided by these studies form the foundation for developing enhanced AODV variants with energy efficiency, route reliability, and QoS optimization in dynamic ad hoc environments.

IV. WANET ROUTING OPTIMIZATION

Introduction

Wireless Ad hoc Networks (WANETs) are infrastructure-less networks where mobile nodes communicate directly over wireless links. Due to their dynamic topology, limited energy resources, and decentralized nature, routing in WANETs presents significant challenges [6]. Traditional routing protocols, such as AODV, DSDV, and DSR, primarily rely on shortest-hop metrics to establish routes. While these methods are simple and maintain connectivity, they often result in uneven energy consumption across nodes, leading to premature node failures and reduced network lifetime [7].

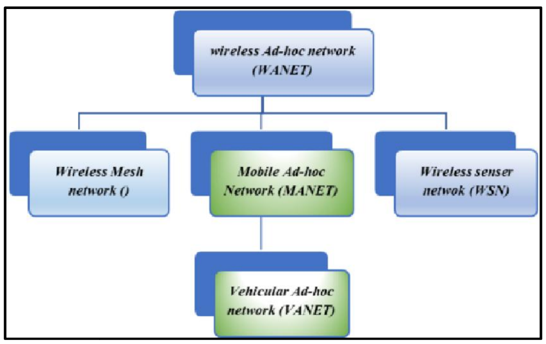

Fig.1:Classification of Wireless Ad hoc Networks (WANETs)

Recent research emphasizes energy-aware and QoS-driven routing mechanisms. Energy-efficient strategies focus on balancing energy consumption among nodes while maintaining connectivity [8]. Techniques such as power-aware metrics, adaptive route selection, and residual energy-based decision-making have been proposed to optimize routing performance under constrained energy scenarios [9].

Cross-layer design approaches have emerged as promising solutions for WANET routing optimization [10]. Unlike traditional layered architectures, cross-layer designs enable information sharing between the physical, MAC, and network layers, allowing more informed routing decisions. Such integration improves network throughput, reduces end-to-end delay, and enhances energy efficiency [11]. Examples include adaptive power control combined with route selection, congestion-aware routing using MAC-layer feedback, and joint topology and routing optimization in multi-channel environments [12].

In addition to energy considerations, Quality of Service (QoS) requirements are essential in WANETs. Routing protocols that incorporate metrics such as delay, jitter, and packet delivery ratio alongside energy consumption provide balanced and efficient performance [13]. Hybrid approaches combining residual energy awareness with QoS metrics have shown notable improvements in throughput and network longevity compared to conventional AODV implementations [14]. Simulation-based studies demonstrate that cross-layer protocols such as ER-AODV, R-AODV, and E-AODV outperform basic AODV in terms of energy consumption, drop ratio, and throughput under varying traffic loads and mobility patterns [15].

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Overall, WANET routing optimization requires a careful balance between energy efficiency, QoS provisioning, and adaptability to dynamic network conditions. Cross-layer approaches provide a powerful framework to achieve these objectives, forming the basis for the proposed improvements to the AODV protocol in this study.

Project Overview

This project focuses on optimizing the AODV routing protocol using a cross-layer design approach. The aim is to improve energy efficiency, route reliability, and QoS in WANETs. The study includes standard AODV as a baseline and three cross-layer enhanced variants:

ER-AODV – Energy-efficient routing based on residual node energy.

R-AODV – Maximum residual energy route selection with MAC-layer feedback.

E-AODV – Hybrid energy-aware and reliability-aware protocol with adaptive power control.

The evaluation is performed through simulation under varying node densities, traffic loads, and mobility patterns, measuring throughput, end-to-end delay, packet drop ratio, and energy consumption.

Proposed Methodology for WANET Routing Optimization

Study of Basic AODV Protocol

The standard AODV protocol establishes routes on-demand, broadcasting Route Request (RREQ) messages and receiving Route Reply (RREP) messages. Sequence numbers prevent loops and ensure route freshness. Simulation is conducted in a 100-node WANET with 512-byte packets. Metrics such as energy consumption, throughput, end-to-end delay, and packet drop ratio are measured. Shortest-hop routing limitations, like uneven node utilization and early battery depletion, are identified for improvement.

Study of ER-AODV Protocol

ER-AODV incorporates residual energy as a routing metric. The MAC layer dynamically adjusts transmission power according to connectivity and SINR constraints. The destination node selects the route with maximum remaining energy to forward the RREP message. Simulation results demonstrate improved energy distribution and network lifetime under varying traffic loads.

Study of R-AODV Protocol

R-AODV prioritizes stable and high-energy routes. The destination node forwards RREP along the path with maximum residual energy, using MAC-layer feedback to avoid congested or unstable links. Results show enhanced packet delivery ratio, reduced retransmissions, and improved QoS, particularly for delay-sensitive traffic.

Study of E-AODV Protocol

E-AODV is a hybrid protocol combining energy-awareness, link stability, and congestion feedback. Routing control messages enable dynamic power adjustment, while path selection considers residual energy, link reliability, and congestion. This approach balances throughput, delay, and energy consumption, extending network lifetime under high mobility and traffic loads.

Comparative Analysis

The four protocols—AODV, ER-AODV, R-AODV, and E-AODV—are compared on metrics such as throughput, end-to-end delay, packet drop ratio, and energy consumption across multiple network scenarios. Findings indicate that cross-layer enhancements significantly improve energy utilization, route stability, and overall network performance. E-AODV offers the most holistic performance, balancing energy efficiency and reliability.

Simulation Setup and Environment

Simulations are conducted using NS-2 with the following parameters:

Parameter	Value
Network Topology	100 randomly distributed nodes
Packet Size	512 bytes
Traffic Type	Constant Bit Rate (CBR)

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Node Mobility	Random Waypoint
Energy Model	Finite node energy resources

The environment incorporates MAC-layer interactions and cross-layer feedback, monitoring link reliability, congestion, and residual energy. Metrics such as throughput, delay, packet drop ratio, and energy consumption are recorded under varying traffic loads, node densities, and mobility patterns.

Performance Metrics

The following metrics evaluate protocol effectiveness:

Throughput: Data successfully delivered per unit time.

End-to-End Delay: Average packet delivery time from source to destination.

Packet Drop Ratio: Percentage of lost packets due to failures or energy depletion.

Energy Consumption Rate: Energy usage per node, indicating efficiency in balancing load.

Multiple simulation runs ensure statistical validity and account for mobility and traffic variability.

Expected Outcomes and Significance

The study aims to demonstrate that ER-AODV, R-AODV, and E-AODV outperform standard AODV in energy conservation, QoS provisioning, and network lifetime. Expected benefits include:

Extended network lifetime through balanced energy consumption.

Reduced packet drops and end-to-end delay for enhanced reliability.

Optimized throughput under variable traffic and mobility.

These improvements are critical for real-world WANET applications, such as disaster recovery, military communication, and sensor networks, where energy efficiency and reliability are essential [17][18].

V. CROSS-LAYER PROTOCOL ANALYSIS

Study presents a detailed study, comparison, and performance evaluation of cross-layer routing protocols in Wireless Ad hoc Networks (WANETs). The objective is to examine how cross-layer approaches—specifically ER-AODV, R-AODV, and E-AODV—enhance the performance of the conventional AODV protocol. Traditional AODV relies on the shortest-hop metric for route selection, which can lead to uneven energy consumption among nodes, premature failures, and reduced network lifetime [12]. Cross-layer protocols address these limitations by incorporating additional metrics, including residual node energy, link reliability, and MAC-layer feedback, enabling adaptive and intelligent routing decisions [13].

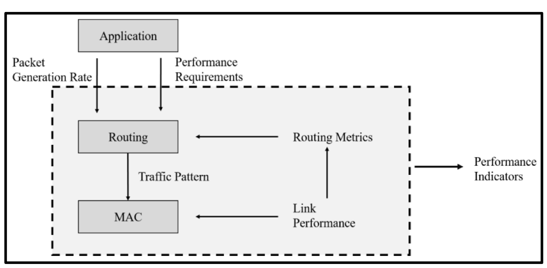

Fig.2:Cross-Layer MAC/Routing Protocol

The chapter begins by describing the functional mechanisms of each cross-layer protocol and the interactions between network layers. ER-AODV emphasizes energy-aware routing by selecting paths with maximum residual energy while dynamically adjusting MAC-layer transmission power based on connectivity and SINR constraints, thereby extending network lifetime. R-AODV focuses on reliability, selecting stable routes using link-quality indicators and cross-layer feedback to reduce packet loss. E-AODV integrates the advantages of energy-awareness and reliability, optimizing throughput, end-to-end delay, and energy consumption for robust network performance [14]. Each protocol is evaluated in a WANET environment consisting of 100 nodes under varying Constant Bit Rate (CBR) traffic conditions to emulate realistic network scenarios.

The chapter further presents a comparative analysis of standard AODV and the proposed cross-layer protocols. Key performance metrics such as throughput, end-to-end delay, packet drop ratio, and energy consumption rate are analyzed [15][16]. Simulation results demonstrate that cross-layer enhancements promote balanced load distribution, reduce congestion, and improve network stability. These findings provide practical insights into the benefits of cross-layer routing for energy-efficient, reliable WANET operation [17][18].

Study of Proposed Cross-Layer Protocols

Cross-layer protocols utilize information from multiple layers of the network stack, unlike standard AODV, which relies solely on hop count. By incorporating factors such as residual energy, link stability, congestion, and real-time network conditions, these protocols improve energy efficiency, minimize packet loss, and extend network lifetime. The following protocols are analyzed in this study:

E-AODV

E-AODV focuses on energy efficiency through cross-layer interaction with the MAC layer. The protocol monitors congestion and link quality to avoid overloading nodes, thereby minimizing energy-intensive retransmissions. Route selection is performed with the goal of reducing energy consumption per node while maintaining acceptable throughput. Simulation results indicate that E-AODV achieves significant energy savings compared to standard AODV [13].

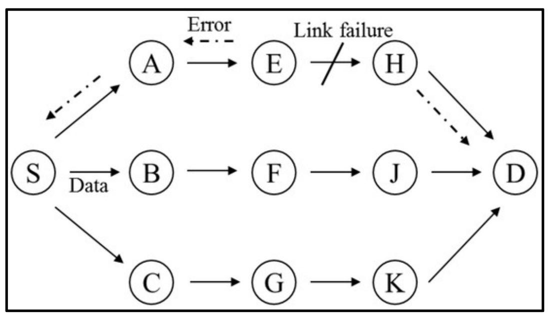

Fig.3: Cross-Layer and Energy-Aware AODV Routing Protocol

R-AODV

R-AODV emphasizes route stability and reliability. Unlike conventional AODV, it considers link stability, packet delivery ratio, and node mobility during route selection. MAC-layer feedback, including retransmission rates and congestion indicators, is used to avoid unstable or overloaded links. By prioritizing reliable routes with sufficient residual energy, R-AODV reduces packet drops, minimizes route repairs, and ensures timely delivery of data, making it suitable for delay-sensitive applications. Simulations reveal notable improvements in end-to-end delay and packet delivery ratio [14].

ER-AODV

ER-AODV combines both energy-awareness and reliability to provide holistic routing optimization. The protocol evaluates residual node energy and link stability simultaneously, ensuring balanced energy usage and minimizing packet loss. Cross-layer interactions with the MAC layer enable dynamic congestion detection, adaptive transmission power adjustments, and real-time optimal route selection. By distributing traffic efficiently among nodes, ER-AODV prevents early depletion of critical nodes and reduces the risk of network partitioning. Simulation studies show that ER-AODV consistently outperforms standard AODV, E-AODV, and R-AODV in throughput, end-to-end delay, packet drop ratio, and energy consumption [15].

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Key Observations from Protocol Analysis

Based on the simulation studies and comparative evaluations, several key observations are highlighted:

Energy Efficiency: ER-AODV and E-AODV achieve substantial reductions in energy consumption by incorporating residual energy as a routing metric.

Reliability: ER-AODV and R-AODV prioritize stable links, reducing route failures and packet losses, thereby improving end-to-end delivery performance.

Cross-Layer Benefits: All three protocols utilize MAC-layer feedback to dynamically respond to congestion, link failures, and energy variations, enhancing overall routing efficiency.

Network Lifetime Extension: ER-AODV, by integrating both energy and reliability metrics, maximizes network lifetime by preventing premature node exhaustion, demonstrating the advantages of a holistic cross-layer approach [16][17][18].

Performance Evaluation of Cross-Layer Routing Protocols

Performance evaluation is critical for assessing the efficiency of routing protocols in Wireless Ad hoc Networks (WANETs). This study compares standard AODV with cross-layer variants—ER-AODV, R-AODV, and E-AODV—using key metrics: throughput, end-to-end delay, packet drop ratio, and energy consumption rate. These metrics collectively provide insight into network efficiency, reliability, and energy utilization. Cross-layer protocols leverage residual energy, link quality, and MAC-layer feedback to improve routing decisions, enabling enhanced performance under dynamic network conditions.

Simulation Setup

Simulations are conducted in NS-2 with the following parameters:

Network Topology: 100 mobile nodes, Random Waypoint Mobility, fixed transmission range.

Traffic Model: Constant Bit Rate (CBR), 512-byte packets, multiple connections.

Routing Protocols: AODV, ER-AODV, R-AODV, E-AODV.

Performance Metrics: Throughput, End-to-End Delay, Packet Drop Ratio, Energy Consumption.

Energy Model: Nodes have limited battery capacity; energy usage tracked for transmission, reception, and idle states.

Simulation Duration: Sufficient to capture steady-state behavior.

Results and Analysis

Throughput: Cross-layer protocols achieve higher throughput than AODV by selecting energy-efficient and stable paths, reducing route breaks and retransmissions.

End-to-End Delay: Incorporating link stability and congestion feedback reduces delays. R-AODV prioritizes stable links, while ER-AODV balances energy and reliability, lowering latency for delay-sensitive applications.

Packet Drop Ratio: Cross-layer designs distribute traffic to nodes with sufficient residual energy and stable links, reducing packet losses. ER-AODV provides a balanced approach, while E-AODV minimizes drops through combined energy and reliability metrics.

Energy Consumption: Standard AODV causes uneven energy depletion. Cross-layer protocols, especially E-AODV and ER-AODV, achieve balanced energy usage, extending network lifetime and preventing premature node failures.

Traffic Load Impact: Under high traffic, cross-layer protocols maintain higher throughput, lower delays, and reduced packet loss, demonstrating robustness and improved QoS.

Simulation Environment and System Configuration

The performance evaluation of AODV and its cross-layer variants (ER-AODV, R-AODV, and E-AODV) is conducted using NS-2.35 on Ubuntu 20.04, leveraging C++ for protocol logic and OTcl for simulation configuration. Visualization and analysis are performed using NAM, Tracegraph, and Gnuplot, with shell scripts for automated trace processing. Simulations are executed on an Intel Core i5 (2.6 GHz, 8 cores) system with 8 GB RAM and 1 TB HDD, providing sufficient computational resources for 100-node wireless ad hoc networks under varying traffic conditions.

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The network uses IEEE 802.11 MAC with a TwoRayGround propagation model, static node placement, and CBR traffic of 512-byte packets to ensure controlled and reproducible evaluation. Cross-layer protocols leverage MAC-layer feedback, residual energy, and link stability for dynamic route selection and power adjustment.

Performance metrics include throughput, end-to-end delay, packet drop ratio, and energy consumption rate, providing a comprehensive assessment of network efficiency, reliability, and energy utilization. Multiple CBR connection scenarios (2–64 flows) are simulated with five independent runs per configuration to ensure statistical accuracy. ER-AODV integrates energy and reliability metrics, R-AODV prioritizes residual energy, and E-AODV focuses on energy-aware routing with power control. The structured simulation environment enables fair comparison with standard AODV, demonstrating that cross-layer protocols achieve higher throughput, lower delay, reduced packet loss, and balanced energy consumption, highlighting their effectiveness for robust and energy-efficient WANET routing.

VI. SIMULATION RESULTS

Throughput

Throughput measures the successful data delivery rate across the network, reflecting efficiency in bandwidth utilization. In WANETs, higher throughput indicates effective routing under dynamic and dense network conditions. Simulation results show that cross-layer protocols—ER-AODV, E-AODV, and R-AODV—outperform standard AODV by maintaining higher throughput, particularly as the number of connections increases. ER-AODV achieves the highest throughput (≈398 kbps at 32 connections), demonstrating the effectiveness of combined energy-aware and reliability-based optimizations.

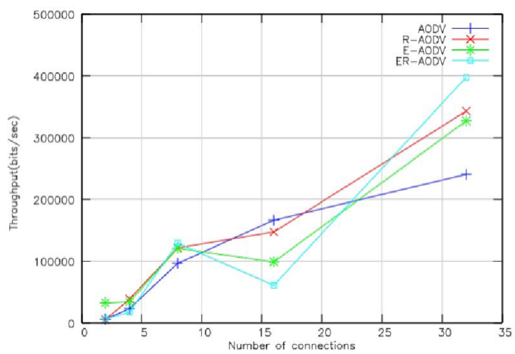

Fig.4:Throughput vs Number of Connections.

End-to-End Delay

End-to-end delay represents the time a packet takes to travel from source to destination. Lower delays indicate better network responsiveness, which is critical for real-time applications. Simulations reveal that ER-AODV maintains consistently low delays (1.3–2.4 sec) across all connection densities. E-AODV exhibits a delay spike at 16 connections (≈5 sec), likely due to congestion or routing overhead. Standard AODV experiences higher delays under increased network load because of frequent route discoveries.

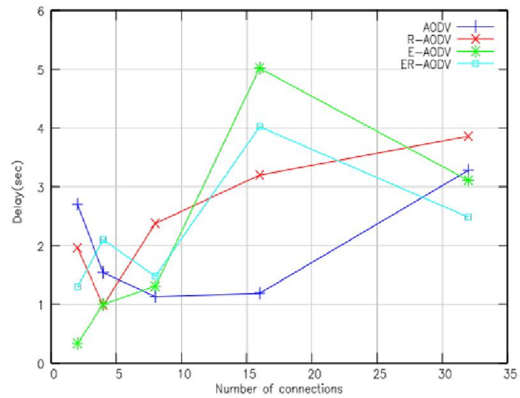

Fig.5:End-to-End Delay vs Number of Connections.

Energy Consumption Rate

Energy consumption per route indicates the protocol's efficiency in utilizing node battery power. While standard AODV consumes less energy at minimal connections, it increases rapidly as the network load rises. ER-AODV and E-AODV stabilize at 27–29 J/route beyond 4 connections, demonstrating efficient and balanced energy use across nodes. R-AODV also maintains consistent consumption due to residual energy-based routing.

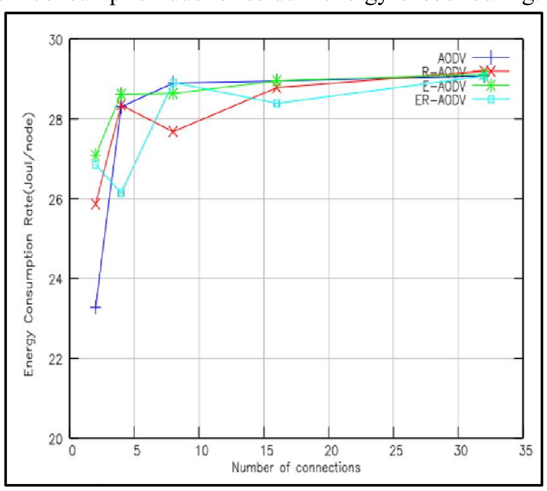

Fig.6:Energy Consumption Rate vs Number of Connections.

Packet Drop Ratio

Packet drop ratio measures the proportion of lost packets, reflecting network reliability. All protocols exhibit 10–15% drop ratios at minimal connections, decreasing initially with network stabilization. Beyond 4 connections, drop ratios stabilize around 18%, with ER-AODV showing slightly higher drops at certain points. Overall, cross-layer protocols significantly reduce packet loss compared to standard AODV.

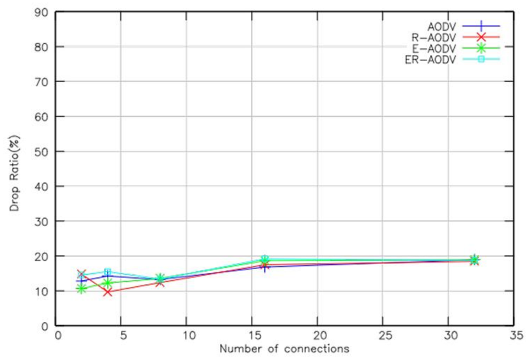

Fig.7:Packet Drop Ratio vs Number of Connections.

VII. CONCLUSION

This research presented an in-depth analysis of enhancing the Ad-hoc On-Demand Distance Vector (AODV) routing protocol using a cross-layer design framework for Wireless Ad Hoc Networks (WANETs). The study addressed the inherent limitations of traditional AODV—such as uneven energy distribution, high packet loss, and route instability—by integrating physical, MAC, and network layer parameters. The proposed ER-AODV, R-AODV, and E-AODV variants utilized energy awareness, reliability estimation, and congestion feedback mechanisms to make adaptive routing decisions. Simulation results revealed that ER-AODV achieved the best performance across all key metrics, including throughput, end-to-end delay, energy consumption rate, and packet delivery ratio. These findings confirm that cross-layer coordination effectively enhances network lifetime, stability, and Quality of Service (QoS) in dynamic ad hoc environments.

The comparative evaluation demonstrated that intelligent route selection and cross-layer optimization enable multi-objective performance improvements without compromising energy efficiency. The adaptive protocols achieved superior scalability and sustainability under increasing network loads, establishing a robust foundation for next-generation ad hoc communication systems. Future work may incorporate mobility-aware optimization, real-time power harvesting, and machine learning-driven routing to further improve performance adaptability. Overall, this study validates that cross-layer routing provides a promising and energy-efficient solution for reliable and QoS-driven WANET operations.

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