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A Cross-Layer Approach to Enhancing the Performance of the AODV Routing Protocol in Wireless Ad Hoc Networks (WANETs)

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Abstract: *Ad hoc networks that do not depend on fixed infrastructure but instead use multi-hop wireless links to communicate are called WANETs. These networks are decentralized and self-configuring. Because of their adaptability, they play a crucial role in emergency response, defense operations, and disaster management. Nevertheless, WANET routing is extremely difficult because of the unpredictable link quality, limited energy resources, dynamic topology, and mobile nodes. Although the Ad hoc On-Demand Distance Vector (AODV) protocol's on-demand route discovery is extensively used, it has a few drawbacks, such as a high energy consumption rate, a high rate of route failures, and limited support for Quality of Service (QoS). By facilitating data exchange between the network, media access control (MAC), and physical levels, this study improves AODV. The three enhanced versions of AODV that are suggested here are ER-AODV, E-AODV, and R-AODV. These versions aim to optimize routing decisions by considering energy metrics, signal strength, and transmission circumstances. The cross-layer variations outperform typical AODV in terms of throughput, latency reduction, packet delivery ratio, and energy consumption, according to NS-2 simulation results. In wireless contexts that are both dynamic and energy-constrained, the results show that cross-layer awareness greatly improves routing efficiency, reliability, and network longevity.*

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

I. INTRODUCTION

Each node in a Wireless Ad Hoc Network (WANET) functions as a host and router, allowing data to be forwarded across multi-hop wireless links. This paradigm has recently arisen as an important one for infrastructure-less and dynamic communication [1, 4]. The quick deployment and scalability of these networks make them ideal for use in mission-critical settings including disaster recovery, military communication, sensor fields, and vehicular systems [5, 7]. The lack of centralized control and the intrinsic mobility of nodes cause topology changes, packet collisions, and route failures frequently, which makes stable and energy-efficient routing a substantial problem [2], [8]. Researchers have provided a number of routing protocols to deal with these issues; one of the most popular is the Ad hoc On-Demand Distance Vector (AODV) protocol, which has received a lot of attention because of its adaptive route discovery process and little control overhead [3], [11]. Even if it's sturdy, AODV still has issues in dense or very mobile networks, such as route instability, high repair latency, and excessive energy consumption [9], [13].

Recent ad hoc routing studies have made energy efficiency and QoS preservation key optimization objectives [14], [16]. Data transmission dependability is determined by quality of service (QoS) metrics including throughput, end-to-end delay, and packet delivery ratio (PDR)[15], [17], whereas network longevity and connectivity are directly impacted by node energy depletion. The capacity to adapt dynamically to changing channel conditions or interference is hindered by conventional AODV routing, which makes decisions mainly at the network layer without coordinating with

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lower layers like the MAC and physical layers [6, 18]. The introduction of cross-layer design concepts has helped to alleviate these limitations[19], [21] by encouraging communication and cooperation across the many OSI model layers in order to improve energy awareness, routing stability, and transmission dependability.

In order to accomplish combined adaptation of power control, link quality estimation, and congestion management, cross-layer optimization frameworks have been thoroughly investigated [20], [22]. Routing techniques that may make use of physical and MAC layer information like signal-to-noise ratio (SNR), residual energy, and node velocity have been shown to significantly increase network lifetime and performance [23], [25]. Power-Aware Routing [14], Energy Conserving Routing [16], and Maximum Lifetime Routing [25] are energy-efficient routing algorithms that emphasize the significance of balancing node energy use to avoid premature node death and network fragmentation. To further reduce retransmissions and latency in different traffic scenarios, AODV has been combined with cooperative link management and adaptive topology control [29], [30].

Data delivery in highly mobile contexts has been improved through recent developments in cross-layer design that prioritize dynamic coordination of routing and MAC protocols [10], [18], [28]. The cross-layer interaction model suggested by Weiss et al. [18] enhances routing performance with real-time MAC feedback, and the energy-aware cross-layer routing proven by Casaquite and Hwang [6] greatly prolongs the operational lifetime of wireless ad hoc networks. To optimize multi-radio mesh networks, Chen et al. [19] also investigated topology management and routing co-design; they achieved better link stability and reduced interference. Research like this shows that conventional on-demand protocols like AODV can benefit from cross-layer intelligence to make them more energy efficient and better suited to new uses like mobile IoT devices and vehicle ad hoc networks in terms of both QoS and energy efficiency.

Despite these advancements, researchers still have not solved the open problem of how to balance cross-layer adaptability with simplicity and scalability of protocols [26], [27]. Additional overhead, synchronization problems, and even breaches of the modularity of the OSI model might result from interactions between protocol layers that are too complicated. Hence, a controllable computationally demanding Enhanced and Reliable AODV (ER-AODV) routing protocol is required to increase route stability, energy consumption, and packet delivery ratio by the use of selective cross-layer feedback. An efficient use of energy and sustained connectivity in extremely dynamic conditions can be achieved with the help of the suggested ER-AODV system, which optimizes route selection using parameters like residual energy, signal strength, and link reliability [17], [20].

This study adds to the existing body of knowledge by creating an improved AODV that spans many layers. It then uses the NS-2 platform to simulate its performance and compares it to both classic AODV and energy-aware variations (E-AODV, R-AODV) [30]. The analysis takes into account different network situations and looks at important performance measures like as energy consumption, packet delivery ratio, end-to-end delay, and throughput. The outcomes reveal that the suggested ER-AODV improves energy economy and routing reliability significantly, proving that next-gen wireless ad hoc networks benefit from cross-layer design [6, 18, 25].

II. PROBLEM STATEMENT

Due to its shortest-path selection and lack of cross-layer awareness, the standard AODV routing protocol in Wireless Ad Hoc Networks has poor QoS support, consumes a lot of energy, and has route failures frequently. For better routing performance, stability, and network longevity in uncertain and resource-limited settings, a new strategy is required that incorporates energy and link-quality data across different levels of the network.

Objectives of study:

- Examine the shortcomings of the conventional AODV routing protocol with regard to QoS, energy efficiency, and route stability.
- Create and deploy three versions of cross-layer enhanced AODV (ER-AODV, E-AODV, and R-AODV) that improve routing decisions by utilizing MAC and physical layer information.
- To use simulation measures like energy consumption, packet delivery ratio, end-to-end delay, and throughput to assess how well the suggested protocols work.

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- Under different network conditions and mobility patterns, evaluate ER-AODV, E-AODV, and R-AODV in comparison to normal AODV.
- To enhance the longevity, dependability, and overall communication efficiency of Wireless Ad Hoc Networks by recommending an optimum cross-layer routing approach.

III. RELATED WORK

The difficulties of wireless ad hoc network design, quality of service provisioning, and energy-efficient routing have been the subject of multiple research. To extend the lifetime of non-homogeneous ad hoc networks, Deying Li, XiaohuaJia, and Hongwei Du [1] studied QoS topology control and proposed algorithms to build topologies that minimize maximum energy consumption among nodes while satisfying traffic and latency restrictions. In contrast to studies of homogeneous networks, their findings stress the significance of achieving a balance in energy use across diverse nodes.

Providers of quality of service in ad hoc networks that use code division multiplexing (CDMA) were the subject of research by Cristina Comaniciu and H. Vincent Poor [2]. Their suggested system for distributed power regulation and routing maximizes the perceived quality of service per transmitted bit by making sure each active link satisfies a specified Signal-to-Interference Ratio (SIR). When contrasted with more traditional power-aware routing techniques, their method proved to be far more energy efficient.

To improve mobile ad hoc networks' throughput and quality of service, Tiantong You, Chi-Hsiang Yeh, and HossamHassanein [3] developed the DRCE MAC protocol. Outperforming standard IEEE 802.11e in terms of average latency, throughput, and priority packet handling, DRCE achieved this by isolating small control packets from large data packets and by reducing hidden and exposed terminal difficulties. The importance of MAC-layer improvements in enhancing network QoS is highlighted in this paper.

It was Charles E. Perkins and Elizabeth M. Royer who first suggested the Ad-hoc On-Demand Distance Vector (AODV) protocol [4]. In dynamic networks, AODV's on-demand route establishment reduces control overhead while simultaneously offering loop-free, swiftly adjustable paths. Standard AODV is responsive and scalable, but it struggles with energy efficiency and route stability when there is a lot of movement. Similarly, the DSDV protocol was created by Perkins and PravinBhagwat [5]. It guarantees loop-free multi-hop routing using sequence numbers, but it can't scale to bigger networks because it relies on periodic updates.

Extensive research has been conducted on energy-aware routing measures. According to research by Suresh Singh et al. [6], power-aware routing can increase node lifetime without causing packet delays and reduce energy usage per packet by as much as 70%. Heuristics such as node-weighted Steiner trees were proposed by Deying Li et al. [7] to reduce overall transmission energy, which is an important consideration for energy-efficient broadcast routing in static networks. To optimize network lifetime while balancing energy consumption among nodes, Jae-Hwan Chang and LeandrosTassiulas [8] introduced flow augmentation and redirection algorithms to prioritize energy-conserving routing in static sensor networks.

Gil Zussman and Adrian Segall [9] investigated energy-efficient routing in disaster recovery and emergency situations, and they developed an anycast routing problem to maximize the time until the first battery drain. Distributed systems that must adhere to stringent energy and bandwidth constraints can find the best solutions with their iterative and polynomial algorithms. As an additional focus, we have highlighted cross-layer design approaches. When combined with congestion-aware routing metrics, adaptive MAC rate selection based on PHY layer information enhances throughput, packet delivery, and end-to-end delay (Ning Yang et al., 2010). In order to improve throughput and decrease co-channel interference, Lin Chen et al. [11] developed a protocol for multiradio multichannel mesh networks called Joint Topology Control and Routing. This protocol coordinates channel selection, power control, and routing.

To increase the lifespan of networks, adaptive energy-based routing strategies have been suggested. In order to improve AODV, LamiaRomdhani and Christian Bonnet [12] used node energy consumption speed to choose routes, which reduced overall energy usage by more than 20% without sacrificing delivery performance. To minimize transmit power while meeting end-to-end assurances, Ulag C. Kozat et al. [13] employed joint power control and scheduling to

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establish a cross-layer framework for energy-efficient communication with QoS provisioning. Power control protocols that maximize energy usage across layers and adjust to traffic load were described by VikasKawadia and P. R. Kumar [14]. These protocols include COMPOW, CLUSTERPOW, MINPOW, and LOADPOW. Lastly, MirghiasaldinSeyedebrahimi and Xiao-Hong Peng [15] examined cross-layer optimization for IEEE 802.11 WLANs. They combined layer adaptation to show significant improvements in throughput and delay by analyzing the joint effects of PHY modulation, MAC retry limits, and APP-layer packet sizes.

All of these studies point to the importance of cross-layer design, quality-of-service provisioning, and energy-aware routing for making wireless ad hoc networks work better and last longer. The findings from these research lay the groundwork for improving AODV variations in dynamic ad hoc situations in terms of energy efficiency, route dependability, and quality of service optimization.

IV. WANET ROUTING OPTIMIZATION

Networks in which mobile nodes communicate with one another directly over wireless links are known as Wireless Ad hoc Networks (WANETs). As a result of their decentralized design, limited energy resources, and changeable topology, WANET routing is quite difficult [6]. It is shortest-hop metrics that are mostly used to create routes by traditional routing protocols like AODV, DSDV, and DSR. Despite their simplicity and ability to keep connections open, these methods frequently cause nodes to consume energy unequally, which in turn shortens the lifespan of the network and causes nodes to break before their time [7].

Routing mechanisms that are energy-aware and motivated by quality of service have recently been the focus of further research. Maintaining connectivity while regulating energy usage across nodes is the aim of energy-efficient techniques [8]. To improve routing efficiency in situations where energy is limited, several methods have been suggested, including power-aware measures, adaptive route selection, and decision-making based on residual energy [9].

In order to optimize WANET routing, cross-layer design techniques have shown promise [10]. By facilitating communication between the physical, media access control (MAC), and network levels, cross-layer systems improve routing decisions over conventional layered architectures. Increased energy economy, decreased end-to-end latency, and better network throughput are all benefits of such integration [11]. Joint optimization of topology and routing in multi-channel situations, adaptive power regulation with route selection, and congestion-aware routing with MAC-layer feedback are all examples [12].

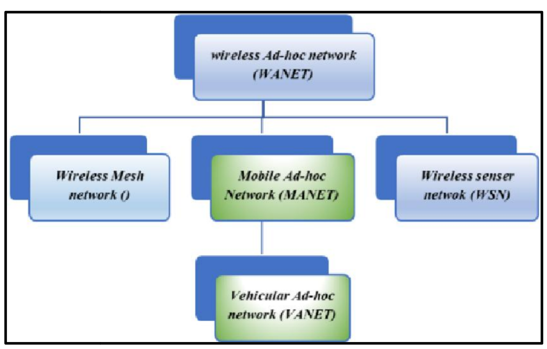

Fig.1:Classification of Wireless Ad hoc Networks (WANETs)

Quality of Service (QoS) needs are crucial in WANETs, alongside energy considerations. Performance is balanced and efficient when routing systems take energy usage into account with measures such packet delivery ratio, jitter, and delay [13]. By integrating QoS measures with residual energy awareness, hybrid systems have outperformed traditional AODV implementations in terms of network lifetime and performance [14]. In terms of energy consumption, drop ratio, and throughput under varied traffic loads and mobility patterns, simulation-based studies show that cross-layer protocols like ER-AODV, R-AODV, and E-AODV perform better than basic AODV [15].

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To optimize WANET routing, one must strike a compromise between three factors: energy efficiency, quality of service provisioning, and responsiveness to changing network conditions. The suggested enhancements to the AODV protocol in this study are based on cross-layer techniques, which offer a strong foundation to accomplish these goals.

Project Overview

The AODV routing protocol is the subject of this project's cross-layer design optimization efforts. Enhanced WANET energy efficiency, route dependability, and quality of service are the end goals. Standard AODV serves as the baseline in this study, along with three versions that have been cross-layer enhanced:

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.

Throughput, end-to-end delay, packet drop ratio, and energy consumption are measured throughout the evaluation, which is carried out through simulation under varied node densities, traffic loads, and mobility patterns.

Proposed Methodology for WANET Routing Optimization

Study of Basic AODV Protocol

Routing Request (RREQ) and Route Reply (RREP) messages are broadcast and received in the standard AODV protocol, which allows routes to be established on-demand. Numbering sequences keeps routes current and eliminates loops. A 100-node WANET using 512-byte packets is used for the simulation. We track things like energy usage, throughput, end-to-end latency, and packet drop ratio. Problems with shortest-hop routing, such as unequal node use and rapid battery drain, are found and addressed.

Study of ER-AODV Protocol

As a routing metric, ER-AODV takes residual energy into account. Transmission power is dynamically adjusted by the MAC layer in response to connection and SINR restrictions. The RREP message is forwarded by the destination node using the route with the most remaining energy. Under different traffic loads, the simulation findings show that the energy distribution and network longevity are both enhanced.

Study of R-AODV Protocol

With R-AODV, stable and high-energy paths are given precedence. In order to avoid unstable or overloaded links, the destination node uses MAC-layer feedback to send RREP down the path with the maximum remaining energy. Particularly for traffic that is sensitive to delays, the results demonstrate an increased packet delivery ratio, fewer retransmissions, and higher quality of service.

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 evaluated in various network scenarios using metrics like throughput, energy consumption, packet loss ratio, and end-to-end delay. According to the results, cross-layer improvements greatly boost network performance, stability of routes, and energy utilization. When it comes to overall performance, E-AODV is unrivaled because to its stability and energy economy.

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

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Traffic Type	Constant Bit Rate (CBR)
Node Mobility	Random Waypoint
Energy Model	Finite node energy resources

Link dependability, congestion, and residual energy are monitored in this environment, which also includes MAC-layer interactions and cross-layer feedback. Under different traffic loads, node densities, and mobility patterns, metrics like energy consumption, packet drop ratio, throughput, and delay are measured.

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

In terms of energy conservation, quality of service delivery, and network lifetime, the study intends to show that ER-AODV, R-AODV, and E-AODV are better than regular AODV. Promising advantages including:

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 enhancements are vital for WANET applications in the real world, like sensor networks, military communication, and disaster recovery, where dependability and energy efficiency are paramount [17][18].

V. CROSS-LAYER PROTOCOL ANALYSIS

This paper examines WANET cross-layer routing protocols in depth, compares them, and evaluates their performance. The goal is to see how the traditional AODV protocol performs when combined with cross-layer techniques, particularly ER-AODV, R-AODV, and E-AODV. An unequal distribution of nodes' energy consumption, early failures, and decreased network lifetime can result from traditional AODV's use of the shortest-hop metric for route selection [12]. By adding additional metrics such as link reliability, residual node energy, and MAC-layer feedback, cross-layer protocols enable adaptive and intelligent routing decisions, therefore addressing these restrictions [13].

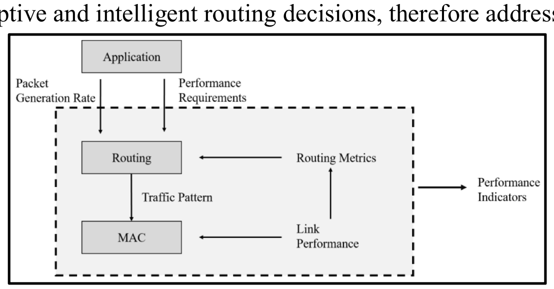

Fig.2:Cross-Layer MAC/Routing Protocol

Understanding the inner workings of each cross-layer protocol and how they interact with one another is the first order of business in this chapter. In order to prolong the lifetime of the network, ER-AODV prioritizes energy-aware routing by choosing paths with the largest residual energy and dynamically modifying the transmission power of the MAC layer according to connectivity and SINR limitations. In order to minimize packet loss, R-AODV prioritizes dependability by choosing stable routes with the use of link-quality indicators and cross-layer feedback. E-AODV optimizes energy usage, end-to-end latency, and throughput for resilient network performance by integrating the benefits of reliability and energy-awareness [14]. In order to simulate real-world network conditions, each protocol is tested in a WANET environment with 100 nodes and varied Constant Bit Rate (CBR) traffic scenarios.

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In addition, the chapter compares and contrasts the suggested cross-layer protocols with conventional AODV. Throughput, end-to-end delay, energy consumption rate, and packet drop ratio are some of the important performance indicators that are examined [15]. [16]. Enhanced network stability, less congestion, and more evenly distributed loads are all outcomes of cross-layer enhancements, according to simulation data. Insights into the advantages of cross-layer routing for energy-efficient and dependable WANET operation are provided by these studies [17]. [18].

Study of Proposed Cross-Layer Protocols

Instead than depending only on hop count, like traditional AODV does, cross-layer protocols use information from many tiers of the network stack. These protocols enhance energy efficiency, reduce packet loss, and prolong the lifetime of the network by considering elements including residual energy, link stability, congestion, and real-time network conditions. For this research, we looked at the following protocols:

E-AODV

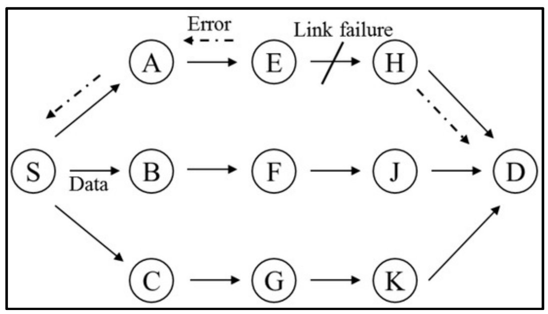

Fig.3: Cross-Layer and Energy-Aware AODV Routing Protocol

By interacting across layers with the MAC layer, E-AODV aims to maximize energy efficiency. In order to minimize energy-intensive retransmissions, the protocol keeps an eye on congestion and link quality to make sure nodes aren't overloaded. Reducing energy consumption per node while maintaining adequate throughput is the purpose of route selection. When compared to conventional AODV, E-AODV is able to save a lot of energy, according to the simulation results [13].

R-AODV

The stability and reliability of the route are prioritized by R-AODV. It differs from traditional AODV in that it takes into account node mobility, packet delivery ratio, and link stability while choosing a route. In order to prevent links from becoming unstable or overcrowded, MAC-layer feedback is utilized. This feedback includes retransmission rates and congestion indications. For applications that are sensitive to delays, R-AODV is the way to go since it prioritizes dependable routes with enough residual energy, which means less packet drops, less route repairs, and on-time data delivery. Both the end-to-end delay and the packet delivery ratio show significant improvements in the simulations [14].

ER-AODV

ER-AODV optimizes routing in a comprehensive way by combining energy-awareness and reliability. To minimize packet loss and maintain balanced energy usage, the protocol simultaneously monitors link reliability and residual node energy. Interactions between layers and the media access control (MAC) layer allow for adaptive transmission power adjustments, real-time optimal route selection, and dynamic congestion monitoring. Reduced likelihood of network partitioning and early depletion of essential nodes are outcomes of ER-AODV's efficient traffic distribution among nodes. According to simulation tests, ER-AODV continuously achieves better results than regular AODV, E-AODV, and R-AODV in terms of energy consumption, packet drop ratio, end-to-end delay, and throughput [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

In order to determine which routing protocols operate best in WANETs, performance evaluation is essential. Throughput, end-to-end delay, packet drop ratio, and energy consumption rate are some of the important metrics used to compare regular AODV with cross-layer versions ER-AODV, R-AODV, and E-AODV. Taken as a whole, these measures shed light on the dependability, efficiency, and energy consumption of the network. To optimize routing decisions and provide increased performance under dynamic network conditions, cross-layer protocols employ residual energy, connection quality, and MAC-layer input.

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.

Simulation Environment and System Configuration

We use NS-2.35 on Ubuntu 20.04 to evaluate the performance of AODV and its cross-layer variations (ER-AODV, R-AODV, and E-AODV). We use C++ for the protocol logic and OTcl for the simulation settings. Using shell scripts for automated trace processing, visualization and analysis are carried out using NAM, Tracegraph, and Gnuplot. A 100-node wireless ad hoc network under different traffic situations can be adequately simulated on an Intel Core i5 (2.6 GHz, 8 cores) PC with 8 GB RAM and 1 TB HDD. A TwoRayGround propagation model, static node placement, and CBR traffic of 512-byte packets are utilized by the network to guarantee controlled and reproducible assessment. To dynamically pick routes and manage power, cross-layer protocols use feedback from the media access control (MAC) layer, residual energy, and link stability.

Throughput, end-to-end delay, energy consumption rate, and packet drop ratio are performance measures that measure the efficiency, dependability, and use of a network. To guarantee statistical accuracy, five separate runs are performed for each configuration to simulate multiple CBR connection scenarios ranging from two to sixty-four flows. Energy-aware routing with power control is the main focus of E-AODV, whereas R-AODV prioritizes residual energy and ER-AODV incorporates reliability and energy indicators. By using the structured simulation environment, we can compare cross-layer protocols to standard AODV and see that they are more effective for energy-efficient and robust WANET routing in terms of throughput, delay, reduction of packet loss, and balance of consumption.

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VI. SIMULATION RESULTS

Throughput

A network's throughput is a measure of how efficiently it uses its available capacity to transmit data to its end users. Increased throughput in WANETs is a sign of efficient routing in congested and dynamic network environments. When compared to regular AODV, the simulation results reveal that ER-AODV, E-AODV, and R-AODV, which are cross-layer protocols, retain a greater throughput, especially when the number of connections increases. By achieving the maximum throughput (about 398 kbps at 32 connections), ER-AODV proves that optimizations based on both energy-awareness and dependability are viable.

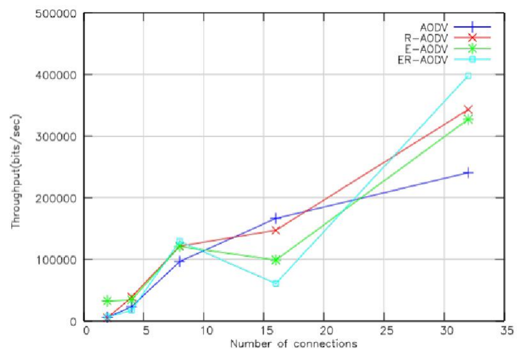

Fig.4:Throughput vs Number of Connections.

End-to-End Delay

Total time a packet spends in transit from origin to destination is called end-to-end delay. For real-time applications, a responsive network with minimal delays is essential. Regardless of the density of connections, ER-AODV always keeps its delays low (1.3-2.4 sec), according to the simulations. It is probable that congestion or routing overhead is to blame for the delay spike (≈5 sec) seen at 16 connections in E-AODV. The increasing network demand causes standard AODV to encounter larger delays due to the frequent route discoveries.

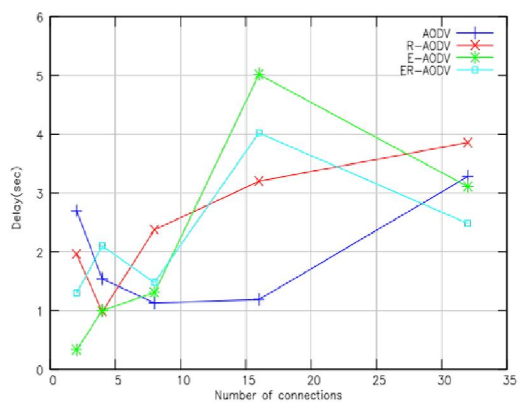

Fig.5:End-to-End Delay vs Number of Connections.

Energy Consumption Rate

The efficiency of the protocol in exploiting the battery power of nodes is indicated by its energy consumption per route. Although the energy consumption of normal AODV is lower at low connection loads, it climbs significantly at high network loads. ER-AODV and E-AODV both reach stability at 27-29 J/route after four connections, showing that the energy consumption across nodes is balanced and efficient. Additionally, R-AODV's usage remains constant because of its residual energy-based routing.

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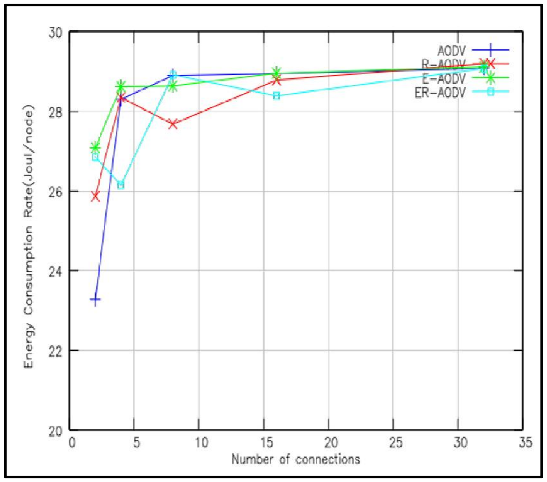

Fig.6:Energy Consumption Rate vs Number of Connections.

Packet Drop Ratio

One indicator of a reliable network is the packet drop ratio, which is the percentage of packets that do not make it through. The drop ratios for low connections for all protocols are 10-15%, and they initially decrease as the network stabilizes. At some stages after four connections, the drop ratios stabilize at about 18%, with ER-AODV exhibiting somewhat greater declines. In comparison to conventional AODV, cross-layer protocols drastically cut down on packet loss.

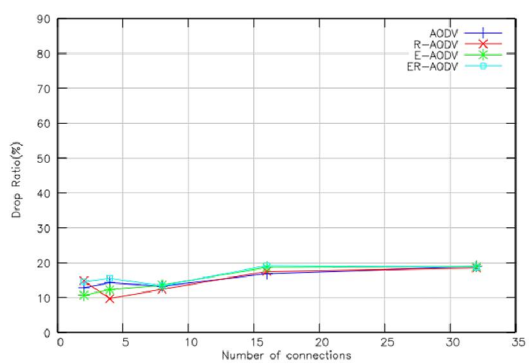

Fig.7:Packet Drop Ratio vs Number of Connections.

VII. CONCLUSIONS

This study provided a comprehensive evaluation of a cross-layer design framework for WANETs as a means of improving the Ad-hoc On-Demand Distance Vector (AODV) routing protocol. Through the integration of physical, MAC, and network layer factors, the study tackled the intrinsic constraints of classical AODV, including uneven energy distribution, high packet loss, and route instability. In order to create adaptive routing decisions, the suggested ER-AODV, R-AODV, and E-AODV variations made use of energy awareness, reliability estimate, and congestion feedback mechanisms. When looking at throughput, end-to-end delay, energy consumption rate, and packet delivery ratio as metrics, the simulation results showed that ER-AODV performed the best. These results show that in dynamic ad hoc settings, cross-layer coordination improves network stability, longevity, and QoS.

Intelligent route selection and cross-layer optimization allow for increases in multi-objective performance that do not compromise energy efficiency, as shown in the comparative study. The adaptive protocols laid a solid groundwork for ad hoc communication systems of the future by achieving better scalability and sustainability under growing network

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demands. To further enhance performance adaptability, future work may add optimization that takes mobility into account, power harvesting in real-time, and routing driven by machine learning. This study confirms that cross-layer routing is an efficient and effective way to ensure dependable and quality-of-service-driven WANET operations.

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