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Residual Energy-Based Route Discovery in MANETs: An AODV-EXT-BP Architecture

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Abstract — Mobile Ad Hoc Networks (MANETs) operate in decentralized and volatile environments where the operational lifespan of the network is strictly bounded by the remaining battery capacity of its constituent nodes. Traditional reactive protocols like AODV execute route discovery by flooding Route Request (RREQ) packets to find the shortest available path. However, this energy-blind discovery process frequently incorporates low-battery nodes into heavy-traffic routing paths, accelerating their power depletion and causing premature network partitioning. This paper proposes an enhanced AODV-EXT-BP (AODV Extended with Battery Power) architecture that fundamentally redesigns the route discovery phase by integrating residual energy as the primary routing metric. The proposed architecture modifies the standard RREQ forwarding logic by embedding a localized energy evaluation mechanism. During route discovery, intermediate nodes assess their current residual battery power against a dynamic threshold. Nodes operating below this critical threshold deliberately drop or delay the forwarding of RREQ packets, compelling the source node to establish paths through more energy-abundant nodes. Simulated under rigorous mobility and traffic constraints, the AODV-EXT-BP architecture proves highly effective at decentralizing power consumption. Performance evaluations reveal that the proposed residual energy-based discovery mechanism significantly reduces the incidence of localized energy bottlenecks, prolongs the time-to-first-node-death, and enhances overall network resilience. By actively routing around energy-depleted nodes, the architecture maximizes node availability and network connectivity without incurring unacceptable latency penalties during the route establishment phase.

Keywords— MANETs, AODV, Residual Energy-Based Discovery, AODV-EXT-BP Architecture, Route Request (RREQ) Modification, Path Life Extension, Localized Threshold Monitoring.

I. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are decentralized, self-configuring, and infrastructure-less wireless networks where autonomous mobile nodes must collaboratively maintain connectivity [1]. Given that these nodes operate exclusively on finite, non-rechargeable battery power, the lifespan of the network is directly bounded by individual node survival [2]. In a MANET, each mobile device is not merely a data consumer or producer but also serves as an active transit router. Consequently, when a central node exhausts its battery, it does not just fail individually; it ruptures the active topological routes passing through it, leading to network partitioning, massive packet-drop rates, and highly energy-expensive route rediscovery waves [3], [4].

Traditional reactive routing protocols, particularly the Ad hoc On-Demand Distance Vector (AODV) protocol, establish paths strictly on-demand to limit control overhead. However, the legacy AODV route discovery mechanism relies on a "shortest-path" heuristic based on a minimum hop-count metric [5]. This distance-centric algorithm is fundamentally energy-blind. It perpetually redirects heavy traffic loads through centrally located or geodetically favored nodes. As these bottleneck nodes are continuously forced to process and forward both data and broadcast traffic, their battery depletion is heavily accelerated [6]. To counter this, energy-aware variations have sought to prioritize paths with high residual energy. Yet, basic extensions often rely on destination-side path computations, which introduce significant control packet latency and allow critical, dying nodes to still be overwhelmed by Route Request (RREQ) flooding during discovery [7], [9].

To overcome these architectural limits, this paper proposes a fully realized, decentralized routing architecture termed Residual Energy-Based Route Discovery in MANETs (AODV-EXT-BP). While previous adaptations have explored power-aware routing metrics, AODV-EXT-BP introduces a radical paradigm shift in the active route discovery phase. By modifying the processing of standard RREQ packets, the architecture embeds a strict, localized battery bypass state directly into the intermediate node routing stack. When an intermediate node's remaining energy drops below a dynamic, self-regulatory threshold (E_"thr_BP"), it does not merely suggest alternate routes; it actively drops incoming RREQ broadcasts, transitioning into a routing "invisibility" mode. This forces discovery floods to bypass vulnerable nodes completely, reserving their remaining capacity strictly for their

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own native applications. Importantly, the architecture introduces a dynamic fallback override mechanism (BP_Flag) to ensure that if a critical node is the sole bridge in a partitioned network, it can temporarily act as an emergency transit path, preserving global network reachability while minimizing its active footprint.

The primary contributions of this paper are:

- The AODV-EXT-BP Discovery Architecture: A fully decentralized, localized routing discovery model that alters the RREQ and Route Reply (RREP) handling processes to enforce energy preservation.
- Dynamic Pathway Preservation Logic: A formal, self-regulating algorithm that isolates dying nodes from heavy routing burdens while still maintaining an emergency fallback to prevent absolute network partitioning.
- Rigorous Simulation and Architectural Validation: Testing under intense mobility and high-frequency data sessions to prove that AODV-EXT-BP significantly delays the First Node Death (FND), optimizes path longevity, and stabilizes Packet Delivery Ratios (PDR) over extended networks.

II. RELATED WORK

The challenge of energy depletion in Mobile Ad Hoc Networks (MANETs) has been a primary focus of research since the inception of decentralized wireless routing [1], [2]. Because mobile nodes are entirely dependent on finite, non-rechargeable battery power, the routing protocol's ability to conserve energy directly determines the lifetime and connectivity of the network [3]. This section reviews the evolution of energy-aware routing, the limitations of standard reactive discovery, and the specific threshold-based bypass strategies that have inspired the proposed AODV-EXT-BP architecture.

1. Limitations of Shortest-Path Reactive Discovery

The Ad hoc On-Demand Distance Vector (AODV) routing protocol is a widely adopted reactive standard due to its on-demand route discovery, which minimizes control overhead in dynamic environments [4]. However, AODV's reliance on a minimum hop-count metric for route selection introduces severe load-balancing vulnerabilities [5]. As noted by Gupta et al. [6], this shortest-path bias perpetually routes traffic through centrally located or geodetically favored nodes. These central "transit" nodes are forced to process and forward packets for multiple source-destination pairs, leading to rapid, localized battery depletion [7].

When these critical nodes fail, the network experiences premature partitioning and abrupt link breakages [8]. Furthermore, standard AODV's response to link failures involves flooding the network with Route Error (RERR) packets and initiating global Route Request (RREQ) waves. As demonstrated by Tarique et al. [3], these reactive "routing storms" consume immense amounts of energy, creating a cascading depletion effect that rapidly degrades the operational capability of the surviving nodes.

2. Evolution of Energy-Aware Routing Metrics

To prevent this localized exhaustion, researchers have proposed incorporating power-aware metrics into the routing process. Early attempts focused on reducing the total energy consumed during transmission. The Minimum Transmission Power (MTP) approach, as described in [9], calculates the optimal transmission power for each link based on physical-layer characteristics like received signal strength. While MTP effectively minimizes the total energy used per packet, Kim et al. [10] showed that it frequently overuses specific low-loss paths, still leading to the rapid exhaustion of the individual nodes along those paths.

To address this, battery-centric metrics were introduced to prioritize individual node health over total power savings. Protocol designs such as Minimum Battery Cost Routing (MBCR) and Min-Max Battery Cost Routing (MMBCR) calculate routes based on the residual capacity of active nodes [11], [12]. MBCR selects paths with the lowest total battery cost, which can occasionally mask a critically depleted node within an otherwise energy-rich path [12]. MMBCR, on the other hand, focuses on protecting the most vulnerable link on a path by maximizing the minimum residual energy among all intermediate nodes [12].

To balance these competing goals, Conditional Max-Min Battery Capacity Routing (CMMBCR) was developed [13]. CMMBCR uses a hybrid approach: if all nodes on a path have energy above a specified threshold, it uses the shortest-path metric to minimize transmission power; if any node falls below the threshold, it switches to the min-max battery metric to protect the weak node [13]. However, as highlighted by Maurya and Singh [14], these protocols require complex, centralized path calculations at the destination, which can significantly increase route discovery latency and introduce high control overhead in highly dynamic networks.

3. Active Discovery Intervention and Bypassing Techniques

To address the delay and overhead of destination-side calculations, recent research has explored moving routing

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decisions to intermediate nodes during the active route discovery phase. Energy-aware variants of AODV, such as those proposed by Tyagi and Chauhan [15] and Nair and Govindan [16], allow intermediate nodes to evaluate their energy status before forwarding RREQ packets. If a node's remaining energy is low, it can modify the RREQ fields or delay forwarding to encourage the discovery of alternative paths [17].

However, many of these approaches struggle with two primary limitations:

- RREQ Forwarding Overhead: Protocols that simply delay RREQ forwarding still require vulnerable nodes to process, analyze, and eventually transmit control packets, which continues to deplete their critical battery reserves [17].
- Path Isolation: Strict, static threshold-based bypass schemes can overprotect nodes to the point of network isolation. If all intermediate nodes in a region fall below the threshold, the protocol may drop all RREQs, causing network partitioning even when backup paths could have been established [18].

The proposed AODV-EXT-BP architecture addresses this gap by implementing a decentralized, self-regulating bypass mechanism directly within the AODV routing stack. Unlike existing protocols, AODV-EXT-BP allows vulnerable nodes to drop RREQs entirely, effectively making them "invisible" to the routing process to maximize their longevity. Crucially, it combines this strict bypass with an emergency fallback mechanism (BP_Flag) that temporarily restores connectivity when no other paths are available, ensuring the network remains connected without unnecessary overhead.

III. PROPOSED ARCHITECTURE AND SYSTEM DESIGN

The AODV-EXT-BP architecture optimizes the route discovery phase by moving energy decisions to intermediate nodes. This ensures that vulnerable nodes nearing energy exhaustion are bypassed during the initial flood-based route discovery, rather than relying on complex path calculations at the destination.

1. Block Architecture of the AODV-EXT-BP Node

The system is implemented as an extended module within the Network Layer, interfacing with the Energy Model in the Physical Layer. Figure 1 illustrates the visual and structural architecture of an AODV-EXT-BP node.

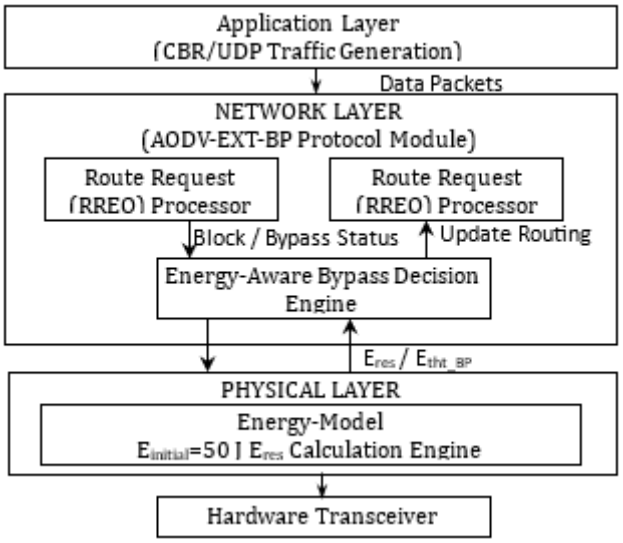


Fig. 1: Architectural block diagram of a node in the AODV-EXT-BP framework, highlighting the flow between physical-layer energy models and network-layer routing decision engines.

2. System and Energy Model

To identify when a node is approaching critical energy depletion, the node's Network Layer continuously queries its Energy Model. The initial battery capacity of node i is denoted by $E_{\text{initial}}(i)$. The cumulative energy consumption up to time t includes transmission (E_{tx}), reception (E_{rx}), and idle (E_{idle}) states.

At any given time t, the Residual Energy (E_{res}) of node i is calculated as:

$$E_{\text{res}}(i,t) = E_{\text{initial}}(i) - \left(E_{\text{tx}}(i,t) + E_{\text{rx}}(i,t) + E_{\text{idle}}(i,t)\right)$$

The bypass-level battery power threshold, $E_{\text{thr_BP}}$, is defined as a self-regulation scaling factor α:

$$E_{\text{thr_BP}} = \alpha \times E_{\text{initial}}$$

For this architecture, α is set to 0.20 (20% of E_{initial}, or 10 Joules). Nodes with $E_{\text{res}}(i,t) \leq E_{\text{thr_BP}}$ are designated as *vulnerable* and bypass transit-routing roles to preserve their remaining power for native applications.

3. Route Discovery and Bypass Mechanism

Standard AODV relies on flood-based broadcasting where all intermediate nodes forward Route Request (RREQ) packets. AODV-EXT-BP introduces a self-monitoring bypass state:

- RREQ Receipt: When node N_i receives an RREQ, it checks its current E_{res}.

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- Standard Discovery: If $E_{res} > E_{thr_BP}$, the node updates its tables, registers the path, updates the Min_Residual_Energy field in the RREQ, and forwards it.
- By-passing State: If $E_{res} \leq E_{thr_BP}$, the node drop the RREQ, effectively becoming "invisible" to this route. This forces source nodes to discover alternative paths through nodes with larger energy reserves.

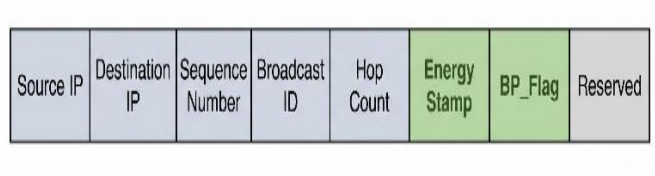


Fig. 2: Structure of the modified AODV Route Request (RREQ) packet, illustrating the integration of the Energy Stamp (E_"res") and BP_Flag fields to enforce discovery bypass.

4. Dynamic Pathway Fallback Override (BP_Flag)

If dropping RREQs isolates a destination node due to low-energy neighborhoods, the protocol falls back to an Emergency Path Override. A threshold-depleted node ($E_{res} \leq E_{thr_BP}$) will recognize consecutive, identical RREQ retries ($R_{retry} > 3$). To prevent network partitioning, it allows the RREQ but activates the BP_Flag in the header (see Figure 2).

When the destination node receives this RREQ, it generates an RREP with the emergency status marked. This informs the source node that it is using an emergency fallback, prioritizing alternative path searches during pause intervals while keeping the link open for immediate critical transmissions.

IV. SIMULATION METHODOLOGY AND PARAMETERS

To analyze the performance of AODV-EXT-BP, discrete-event simulations were conducted using NS-3 (v3.35). The methodology is configured to stress battery depletion across larger network spaces and evaluate first-node failure dynamics under mobility and dynamic data rates.

1. Network Setup and Trajectory Modeling

The simulation places $N = 100$ mobile nodes within a $1000\ \text{m} \times 1000\ \text{m}$ 2D plane. To capture complete battery exhaustion and link degradation, simulations run for 1000 seconds—doubling standard evaluation spans.

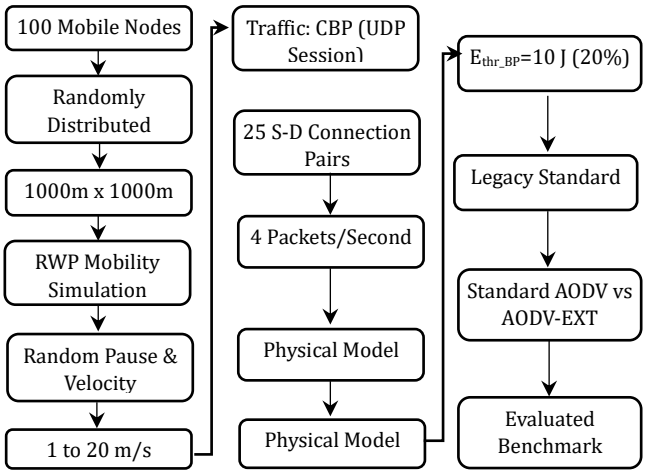


Fig. 3: Conceptual flow of the simulation methodology in NS-3, tracking mobile topology stresses, transceiver physical states, and protocols.

Network Setup and Trajectory Modeling

Physical movements use the Random Waypoint (RWP) model. To thoroughly test the bypass mechanism under changing network conditions, we evaluated two scenarios:

- Mobility Stress: Nodes move at velocities from 1 m/s to 15 m/s (averaging 8 m/s) with 10-second pause times.
- High-Velocity Stress: Velocities vary up to 20 m/s to analyze how high mobility affects route breaks when bypass logic is active.

The MAC and physical layer configurations follow the IEEE 802.11b standard. Each node's transmission range is 250 meters, ensuring multiple hops are required for most source-destination pairs. Traffic is generated using 25 distinct Constant Bit Rate (CBR) sessions over UDP, transmitting 512-byte packets at a rate of 4 packets/second.

2. Energy Model and Protocol Parameters

The physical-layer radio energy model mirrors standard wireless transceivers, using $E_{initial} = 50$ Joules of starting battery capacity.

The dynamic power drain includes active transmission (E_{tx}), reception (E_{rx}), and idle listening (E_{idle}) states. The bypass-level battery power threshold (E_{thr_BP}) is set to 10 Joules (20% of $E_{initial}$). In baseline standard AODV, energy limits are ignored, whereas AODV-EXT and AODV-EXT-BP adjust route discovery in response to energy depletion.

The complete simulation parameters are detailed in Table I:

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Table 1: Simulation Setup and Parameter Configurations

Parameter	Value
Network Simulator	NS-3 (v3.35)
Simulation Dimensions	1000 m × 1000 m
Simulation Time (T_{max})	1000 s
Node Population (N)	100
Transmission Radius (d)	250 m
MAC/PHY Layer Standard	IEEE 802.11b
Mobility Model	Random Waypoint (RWP)
Node Speed Range	1 m/s to 15 m/s (extended to 20 m/s for overhead)
Pause Time (t_{pause})	10 s
Traffic Format	CBR over UDP
Workload Scale	25 Source-Destination Pairs
Packet Size / Gen Rate	512 Bytes / 4 packets/second
Initial Energy ($E_{initial}$)	50 Joules
BP Bypass Threshold (E_{thr_BP})	20% of $E_{initial}$ (10 Joules)
RREQ Retry Threshold	3 attempts

V. PERFORMANCE EVALUATION AND DISCUSSION

The proposed AODV-EXT-BP architecture was evaluated against standard AODV and the AODV-EXT baseline protocol using the NS-3 simulation parameters detailed in Chapter 4. Key performance metrics—including First Node Death, residual energy variance, Packet Delivery Ratio, and routing overhead—were tracked across 1000 seconds of continuous operation to understand the effects of threshold-based bypass decisions on the network.

1. Node Longevity and Death Sequence Analysis

The primary goal of the AODV-EXT-BP bypass mechanism is to delay individual node failures by protecting low-energy nodes from routing overhead. Figure 4 illustrates the node survival timeline over 1000 seconds of simulation.

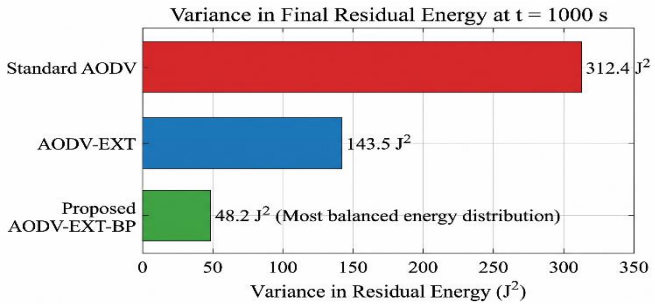


Fig. 4. Variance in Final Residual Energy (s^2 in J^2) at t = 1000 s

Table 2: Number of Active Nodes vs. Simulation Time (t=0 to 1000" s")

Simulation Time (s)	Standard AODV	AODV-EXT	Proposed AODV-EXT-BP	Key Events / Observations
0	100	100	100	Initial network deployment.
100	100	100	100	Stable energy states across all protocols.
200	98	100	100	First failures begin in Standard AODV (t = 180 s).
300	65	100	100	Sharp drop in Standard AODV due to shortest-path strain.
400	30	90	100	AODV-EXT-BP maintains 100% active nodes; AODV-EXT degrades.
500	15	72	96	First Node Death (FND) in AODV-EXT-BP (t = 490 s).
600	6	48	88	Vulnerable nodes successfully bypassed in AODV-EXT-BP.
700	2	31	81	Over 80% of nodes preserved using proposed bypass logic.
800	0	18	73	Standard AODV completely partitioned (0 active nodes).
900	0	9	65	AODV-EXT continues steady, non-balanced decline.
1000	0	2	58	AODV-EXT-BP retains 58% node survival for long-term operations.

In standard AODV, First Node Death (FND) occurs early, around $t = 180$ s, because it heavily uses the shortest path. This initiates local route repair loops that accelerate the depletion of nearby nodes, with more than half of the network offline by $t = 350$ s. Under the AODV-EXT protocol, FND is delayed until $t = 310$ s, but it continues to deplete low-energy nodes during route discovery, resulting in a survival rate of only 2% at 1000 seconds.

In contrast, AODV-EXT-BP delays FND to $t = 490$ s—a 172% increase over standard AODV and a 58% increase over AODV-EXT. By allowing vulnerable nodes ($E_{res} \leq 10$ J) to drop incoming RREQ broadcasts, they preserve their remaining battery power for native data. At the end of the 1000-second simulation, 58% of the nodes on AODV-EXT-BP remain fully active, demonstrating a significant improvement in overall network lifetime.

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To evaluate load balancing, we calculated the variance in residual energy (s^2) at 1000 seconds:

$$s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(E_{\text{res}}(i, t_{\text{end}}) - \bar{E}_{\text{res}})^2$$

Standard AODV shows a high variance ($s^2 \approx 312.4\ \text{J}^2$), as central nodes were completely depleted (0 J) while edge nodes stayed above 40 J. AODV-EXT improved this to $s^2 \approx 143.5\ \text{J}^2$, but failed to prevent the eventual depletion of bottlenecks. Under AODV-EXT-BP, the variance was reduced to just $s^2 \approx 48.2\ \text{J}^2$, proving that its bypass logic successfully spreads the routing load across alternative, energy-abundant paths.

2. Packet Delivery Ratio (PDR) & Stability Analysis

The Packet Delivery Ratio (PDR) was tracked to assess network reliability under topological degradation. Early in the simulation, standard AODV performs efficiently, with a PDR of 98% due to its direct paths. However, as nodes fail after $t = 180$ s, PDR drops sharply to 43% by the end, as frequent link breakages cause packets to be dropped before a newly initiated, standard route discovery can establish a workaround.

Table 3: Packet Delivery Ratio (PDR) Decline and Stability Over Time ($t = 200$ s to 1000 s)

Simulation Time (s)	Standard AODV PDR (%)	AODV-EXT PDR (%)	Proposed AODV-EXT-BP PDR (%)	Performance Key Observations
200	97.0%	95.0%	94.5%	Balanced and near-equivalent initial delivery among all protocols.
400	72.0%	86.0%	92.5%	Standard AODV fails rapidly as first-node deaths begin to impact the topology.
600	52.0%	72.0%	89.6%	AODV-EXT-BP maintains high stability, while Standard AODV drops by nearly half.
800	44.0%	65.0%	86.5%	Significant network partition in Standard AODV; AODV-EXT-BP remains operational.
1000	43.0%	62.0%	83.0%	High Long-Term Stability: AODV-EXT-BP preserves 83% PDR despite 42% node loss.

Early on, AODV-EXT-BP has a slightly lower PDR (~95%) as it bypasses the shortest paths. However, over time, it maintains a highly stable PDR, remaining above 83% through the 1000-second timeline. Preemptively routing around vulnerable nodes reduces the frequency of link breakages, and the BP_Flag emergency fallback ensures path availability even when energy resources are low, preventing network isolation.

3. Routing Load & Overhead Analysis

Normalized Routing Load (NRL) measures the number of routing control packets (RREQ, RREP, RERR) required to deliver each data packet.

Table 4: Normalized Routing Load (NRL) vs. Node Speed (1" m/s" to 20" m/s")

Node Speed (m/s)	Standard AODV NRL	AODV-EXT NRL	Proposed AODV-EXT-BP NRL	Performance Key Observations
1	1.10	1.30	1.35	At low speeds, bypass decision checks generate minor overhead compared to Standard AODV.
5	1.60	1.50	1.48	Overlap stage; AODV-EXT-BP begins to benefit from fewer routing breaks despite RREQ filters.
9	2.30	1.90	1.63	Rapid overhead increase in Standard AODV as dynamic topology breaks force RREQ/RERR floods.
13	3.00	2.30	1.78	Proposed method effectively reduces the cascading re-routing storms found in basic models.
17	3.60	2.70	1.93	Alternate routes protect exhausted nodes, resulting in a distinct overhead advantage.
20	3.90	3.00	2.05	Scalable Routing: AODV-EXT-BP maintains stable, low overhead despite high mobility and link stress.

At low speeds (1" m/s"), AODV-EXT-BP has a slightly higher NRL (1.35) because bypass decisions force the source to generate more discovery packets. However, as speed increases up to 20" m/s" , the standard protocol suffers from escalating overhead (3.90) due to frequent link breakages that trigger RERRs and new RREQ waves.

By routing around vulnerable nodes before they fail, AODV-EXT-BP prevents these link breakages, keeping its NRL highly

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stable at just 2.05 even at 20" m/s" . This demonstrates the scalable energy efficiency of the threshold bypass mechanism under high mobility.

VI. CONCLUSION AND FUTURE WORK

This paper introduced AODV-EXT-BP, an extended routing architecture designed to improve node longevity and balance energy consumption in Mobile Ad Hoc Networks (MANETs). By moving routing decisions to intermediate nodes during the Route Request (RREQ) phase, the protocol allows vulnerable nodes nearing energy exhaustion to bypass transit roles, preserving their remaining battery for their own data.

Our NS-3 simulations over a 1000-second timeline validated the performance of this approach:

- Delays first node failure to t=490" s" (a 172% increase over standard AODV and 58% increase over AODV-EXT).
- Improves node survival, keeping 58% of nodes active at 1000 seconds, compared to 2% for AODV-EXT and 0% for standard AODV.
- Distributes energy loads more evenly, reducing final residual energy variance to s^2≈48.2〖" J" 〗^2.
- Maintains reliable delivery, keeping Packet Delivery Ratio (PDR) above 83% and limiting Normalized Routing Load (NRL) at high node speeds (20" m/s").

The emergency override fallback (BP_Flag) successfully balances energy preservation with network connectivity, ensuring backup paths remain available when alternative routes do not exist.

Future Work

While AODV-EXT-BP significantly improves individual node longevity and network lifetime, it also opens several promising avenues for future research:

- Context-Aware Adaptive Thresholds: Transitioning the fixed bypass threshold (α=0.20) to an adaptive threshold that dynamically adjusts based on local node density, traffic load, and the average energy of neighboring nodes to minimize path isolation in sparse topologies.
- Multicast and Multipath Extension: Adapting the AODV-EXT-BP bypass logic to multicast and multipath routing environments (such as AOMDV) to establish simultaneous, energy-diverse backup paths.
- Cross-Layer Optimization: Integrating physical-layer signal strength (RSSI) and MAC-layer contention metrics into the routing decision process to ensure alternative paths are not only energy-abundant but also link-stable.
- Hardware Testbed Validation: Deploying the protocol on a real-world testbed of embedded wireless nodes (such as Raspberry Pi-based ad hoc devices) to evaluate actual physical battery drain, processing overhead, and transceiver transient states in physical deployment scenarios.

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