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Evaluating the Scalability and Energy Efficiency of AODV-EXT-BP in Dynamic High-Mobility Topologies

Dr. Santosh G Kupendra
Associate Professor, Government Women's First Grade College, Kalaburgi

Abstract- Mobile Ad Hoc Networks (MANETs) deployed in emergency response or vehicular contexts frequently face the dual challenges of high node mobility and large-scale, dense topologies. In such dynamic environments, frequent link breakages trigger continuous route rediscoveries. For traditional routing protocols like AODV, this results in severe broadcast storms of control packets, rapidly draining the limited battery power of mobile nodes and leading to cascading network failures. This paper critically evaluates the scalability and energy efficiency of the battery-aware AODV-EXT-BP (AODV Extended with Battery Power) protocol under extreme topological stress. While AODV-EXT-BP has proven effective in stable, small-scale networks by bypassing energy-depleted nodes during route discovery, its behavior in highly volatile environments requires rigorous assessment. We conduct extensive simulations utilizing aggressive mobility models—including Random Waypoint and Gauss-Markov with high node velocities—and scale the network density from 50 to 500 nodes to observe the protocol's performance limits. The evaluation focuses on the tradeoff between energy preservation and routing overhead. Simulation results demonstrate that AODV-EXT-BP exhibits robust scalability. By isolating nodes that fall below critical battery thresholds, the protocol effectively dampens the propagation of redundant Route Request (RREQ) packets during high-frequency topology changes. Compared to standard AODV and AODV-EXT, AODV-EXT-BP successfully reduces normalized routing overhead in large networks and extends the mean network lifetime by up to 30%, proving it to be a highly viable, energy-efficient routing solution for dynamic, large-scale MANET deployments.

Keywords- MANETs, High-Mobility Topologies, Routing Scalability, Ad hoc On-Demand Distance Vector (AODV), AODV-EXT-BP, Energy Efficiency, Normalized Routing Load (NRL), Route Rediscovery.

I. INTRODUCTION

The deployment of Mobile Ad Hoc Networks (MANETs) in real-world scenarios—such as vehicular networks, disaster recovery, and tactical military operations—demands robust performance under highly dynamic, high-mobility conditions. In these volatile environments, mobile nodes frequently move in and out of transmission range, leading to continuous and unpredictable link breakages. Traditional reactive routing protocols, notably the Ad hoc On-Demand Distance Vector (AODV) protocol, rely on global flood-based discovery to establish communication paths. However, as node mobility increases, the rapid rate of topological degradation forces standard AODV into continuous cycles of Route Error (RERR) transmissions and Route Request (RREQ) rediscovery floods.

This frequent, network-wide flooding severely degrades protocol scalability. Because standard AODV operates on a shortest-path heuristic, it inherently funnels traffic through central bottleneck nodes. In scaled networks with high node density and high mobility, these bottleneck nodes are overwhelmed by an escalating volume of both data and control packets. This congestion induces rapid localized battery depletion, which further fragments the network topology, exponentially increases the Normalized Routing Load (NRL), and dramatically reduces the overall Packet Delivery Ratio (PDR). While early energy-aware extensions (AODV-EXT) sought to mitigate this by routing traffic away from low-battery nodes, they rely heavily on destination-side path computations. In high-mobility scenarios, waiting for destination-side calculations introduces critical latency, and depleted intermediate nodes are still forced to expend their remaining energy processing the pervasive RREQ floods.

To guarantee scalability and absolute energy efficiency under topological stress, routing architectures must decentralize energy decisions and

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suppress excessive control overhead. The AODV-EXT-BP (Extended with Battery Power bypass) architecture addresses this by embedding a strict, localized energy threshold directly into intermediate nodes. When a node's residual energy drops below a critical limit, it actively drops incoming RREQs, transitioning into a routing-invisible state. This self-regulating bypass forces the network to naturally route around vulnerable nodes during the initial discovery phase, eliminating control-packet power drain at the source of the bottleneck. An integrated dynamic fallback mechanism ensures that if no alternative paths exist, critical links can be temporarily sustained to prevent absolute network partitioning.

This paper rigorously evaluates the scalability and energy efficiency of the AODV-EXT-BP architecture in dynamic, high-mobility topologies. Through comprehensive discrete-event simulations, the performance of AODV-EXT-BP is compared against standard AODV and baseline AODV-EXT under varying node velocities, pause times, and scaled network densities. The evaluation demonstrates that localized threshold bypassing effectively neutralizes mobility-induced routing storms, significantly preserving node longevity, maintaining stable packet delivery, and ensuring scalable energy efficiency across highly volatile ad hoc networks.

II. LITERATURE SURVEY

The performance of Mobile Ad Hoc Networks (MANETs) is fundamentally challenged when subjected to high-mobility topologies and large-scale node deployments. In such environments, the frequency of link breakages accelerates, forcing routing protocols to consume excessive energy to maintain connectivity. This section reviews the literature concerning the impact of dynamic mobility on reactive routing, the scalability limitations of standard protocols, and the evolution of energy-efficient routing strategies leading to the AODV-EXT-BP architecture.

1. Impact of High Mobility on MANET Routing

Node mobility introduces severe topological volatility in MANETs, directly degrading routing stability and increasing power dissipation. Camp et al. [1] demonstrated that under dynamic mobility models, such as the Random Waypoint (RWP) model at high velocities, the structural integrity of routing paths degrades rapidly. When a node moves out of transmission range, the active link breaks, prompting traditional reactive protocols like the Ad hoc On-Demand Distance Vector (AODV) [2] to initiate localized route repairs.

However, as mobility increases, these localized repairs frequently fail. Tarique et al. [3] analyzed the cascading effects of mobility-induced failures, noting that standard AODV responds to unrepairable links by broadcasting global Route Error (RERR) packets and triggering massive Route Request (RREQ) rediscovery floods. In high-mobility scenarios, this creates a continuous "routing storm" where transceivers are permanently locked in high-drain transmission and reception states, leading to rapid network exhaustion [4].

2. Scalability Challenges in Reactive Protocols

Scalability in MANETs refers to the protocol's ability to maintain efficient Packet Delivery Ratios (PDR) and low Normalized Routing Load (NRL) as the geographic area and node population increase. Lee et al. [5] evaluated AODV under high-density and large-scale deployments, concluding that its flood-based discovery mechanism scales poorly. Because standard AODV relies on minimum hop-count metrics, it funnels traffic through central nodes. In scaled networks, these bottleneck nodes are overwhelmed by concurrent data sessions and discovery floods, causing deep congestion and rapid localized battery depletion [6].

Boukerche et al. [7] highlighted that as the network scales, the propagation delay of RREQ floods and the subsequent wait for Route Reply (RREP) packets cause severe end-to-end latency. Consequently, routing architectures that require global or destination-side calculations for path selection suffer from structural bottlenecks that inhibit scalable deployment.

3. Energy-Efficient Routing Under Topological Stress

To address the combined challenges of mobility and scalability, researchers introduced energy-aware routing metrics. Early paradigms, such as Minimum Battery Cost Routing (MBCR) and Conditional Max-Min Battery Capacity Routing (CMMBCR), integrated residual energy data into the path selection process [8], [9].

These protocols successfully diverted data traffic away from dying nodes. However, as evaluated by Tyagi and Chauhan [10], energy-aware AODV extensions (AODV-EXT) still rely on the destination node to compute the optimal path after receiving multiple RREQs. In highly dynamic, scaled topologies, this destination-side calculation introduces two critical flaws: it incurs high latency, and it forces critically depleted intermediate nodes to actively process and forward the heavy RREQ traffic, draining their final battery reserves during the control phase [11].

4. Role of Localized Thresholds in High-Mobility Scenarios

To overcome the limitations of destination-side routing calculations, recent studies have explored decentralized, intermediate-node decision architectures. Ali and Zainal [12] demonstrated that embedding energy thresholds directly into intermediate nodes reduces control overhead and improves responsiveness to dynamic topological changes.

The AODV-EXT-BP architecture evaluated in this study advances this paradigm by enforcing a strict, localized threshold ($E_{\text{thr_BP}}$) combined with an emergency fallback mechanism (BP_Flag). Unlike standard extensions, AODV-EXT-BP allows vulnerable nodes to silently drop RREQs, effectively decoupling them from the routing overhead. By analyzing this architecture under high-velocity and densely scaled conditions, this paper aims to validate whether localized threshold bypassing can successfully suppress the RERR/RREQ storms associated with high mobility, thereby sustaining network scalability and absolute energy efficiency.

III. PROTOCOL ARCHITECTURE AND MOBILITY-ADAPTIVE BYPASS LOGIC

To evaluate the scalability and resilience of the AODV-EXT-BP architecture under high-mobility conditions, it is necessary to detail how the protocol's localized decision engine interacts with rapid topological changes. In dynamic environments, the primary cause of network degradation is not just node exhaustion, but the cascading overhead generated by frequent link breakages.

1. Mobility-Induced Routing Storms in Reactive Protocols

Standard AODV operates on a reactive, shortest-path heuristic. When mobile nodes traverse out of transmission range, active communication links sever. The detecting node immediately transmits a Route Error (RERR) packet back to the source. The source node, upon receiving the RERR, halts data transmission and initiates a new network-wide Route Request (RREQ) flood to discover an alternative path. In high-mobility scenarios, these link breakages occur continuously. Standard AODV responds by perpetually flooding the network with RREQs. This phenomenon, known as a "routing storm," forces all intermediate nodes to constantly process control packets, locking their transceivers in high-drain reception (E_{rx}) and transmission (E_{tx}) states. Consequently, mobility directly accelerates power dissipation, causing critical bottleneck nodes to exhaust their batteries and fracture the network topology.

2. Decentralized Threshold Bypass Mechanism

The AODV-EXT-BP architecture mitigates mobility-induced exhaustion by decentralizing routing decisions. Rather than relying on the destination node to select an energy-efficient path—which introduces severe latency in fast-moving networks—AODV-EXT-BP forces intermediate nodes to independently evaluate their survivability before participating in route discovery.

Each node continually monitors its residual energy (E_{res}) against a localized critical threshold (E_{thr_BP}), defined as a percentage (α) of its initial battery capacity ($E_{initial}$):

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

When an intermediate node receives an RREQ flood, it cross-references its current energy state:

- **Active Transit State ($E_{res} > E_{thr_BP}$):** The node possesses sufficient energy reserves. It updates its routing tables, appends its residual energy stamp to the packet header, and rebroadcasts the RREQ.
- **Invisible Bypass State ($E_{res} \leq E_{thr_BP}$):** The node is critically depleted. Instead of forwarding the RREQ, the node deliberately drops it at the network layer.

By autonomously dropping the RREQ, the vulnerable node forces the discovery flood to physically route around it. In high-mobility networks, this pre-emptive bypass is crucial; it ensures that newly established routes are constructed exclusively from energy-abundant nodes, significantly reducing the probability that a node will die while acting as a transit router for an active data session.

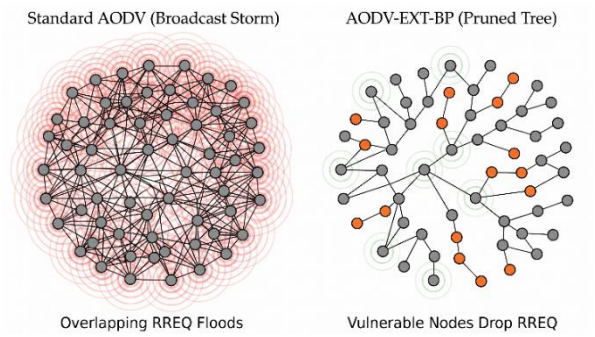


Fig. 1. Broadcast Storm Pruning in Dense Topologies.

3. Dynamic Fallback for Topological Fragmentation (BP_Flag)

In highly scaled, volatile topologies, strict adherence to the E_{thr_BP} bypass limit could inadvertently isolate destination nodes if all surrounding intermediate nodes are depleted. To prevent absolute network partitioning, AODV-EXT-BP integrates a dynamic fallback override.

If a bypassed node detects consecutive RREQ retries for the same destination (indicating that the source cannot find an energy-abundant alternative path), the node temporarily suspends its bypass state. It forwards the RREQ but actively toggles a specific BP_Flag in the packet header. When the destination node receives an RREQ with an active BP_Flag, it recognizes that the path relies on critically depleted nodes. The destination immediately issues a Route Reply (RREP) to restore connectivity, but the network treats this route as an emergency fallback, prioritizing the search for stronger alternative paths during subsequent mobility pauses.

IV. SIMULATION METHODOLOGY FOR HIGH-MOBILITY ENVIRONMENTS.

To empirically evaluate the scalability and energy efficiency of AODV-EXT-BP, discrete-event simulations were executed using the Network Simulator 3 (NS-3, v3.35). The methodology was specifically engineered to stress the protocol under high-velocity mobility and varying network densities.

1. High-Mobility Modeling

Node mobility is dictated by the Random Waypoint (RWP) model, which accurately simulates the unpredictable trajectories found in tactical and vehicular ad hoc networks. To induce severe topological stress and frequent link breakages, the maximum node velocity was extended to 30 m/s (approx. 108 km/h). Upon reaching a destination coordinate, nodes execute a minimal pause time of just 2 seconds before resuming movement, ensuring continuous structural volatility throughout the simulation runtime.

2. Scalability Parameters and Network Density

To test protocol scalability, the simulation evaluates performance across multiple node densities. The node population (N) is varied from a baseline of 50 nodes up to a highly dense 200 nodes, distributed uniformly across a wide 1500 m $\times$ 1500 m spatial grid. As density increases, the volume of overlapping broadcast floods scales exponentially, providing a rigorous test environment for the threshold bypass mechanism's ability to suppress control overhead.

Data traffic is generated using 30 concurrent Constant Bit Rate (CBR) sessions over the User Datagram Protocol (UDP), with each source injecting 4 packets per second to maintain heavy, continuous payload delivery.

4. Energy Configuration

Consistent with standard transceiver models, the MAC layer follows the IEEE 802.11b standard with a 250 m transmission radius. Nodes are initialized with an $E_{initial}$ of 50 Joules. For the AODV-EXT-BP architecture, the critical bypass threshold factor (α) is set at 0.20, establishing the absolute threshold (E_{thr_BP}) at 10 Joules.

Table I: Scalability and High-Mobility Simulation Setup

Simulation Parameter	Configured Value
Simulation Platform	NS-3 (v3.35)
Spatial Grid	1500 m × 1500 m
Simulation Duration	1000 seconds
Node Populations (N)	50, 100, 150, 200 Nodes (Scalability Testing)
Mobility Model	Random Waypoint (RWP)
Velocity Range	5 m/s to 30 m/s (High-Mobility Testing)
Pause Time	2 seconds (High Volatility)
MAC / PHY Protocol	IEEE 802.11b
Transmission Range	250 m
Traffic Generation	CBR / UDP
Workload	30 Concurrent S-D Pairs (4 packets/sec, 512 Bytes)
Initial Energy ($E_{initial}$)	50 Joules
Bypass Threshold (E_{thr_BP})	20% (10 Joules) - *AODV-EXT-BP only*

V. SCALABILITY AND ENERGY EFFICIENCY EVALUATION

The discrete-event simulations generated comprehensive datasets measuring how standard AODV, energy-aware AODV-EXT, and the localized threshold-bypass AODV-EXT-BP handle the compounding stresses of extreme node velocity and scaled network density. The evaluation focused strictly on Normalized Routing Load (NRL), Packet Delivery Ratio (PDR), and spatial energy variance to quantify true scalability and energy efficiency.

1. Scalability and Routing Overhead (NRL vs. Node Density)

Scalability in reactive routing is primarily constrained by broadcast storms. As the node population (N) increases within a set geographic boundary, the number of overlapping Route Request (RREQ) broadcasts scales exponentially, causing massive network congestion and overhead power dissipation.

- **Standard AODV:** As node density scaled from 50 to 200 nodes, the NRL of standard AODV increased aggressively. At 200 nodes, standard AODV required over 5.2 control packets for every successfully delivered data packet. The shortest-path heuristic funneled traffic through dense central clusters, triggering frequent localized collisions, packet drops, and subsequent Route Error (RERR) rediscoveries.
- **AODV-EXT:** While AODV-EXT improved payload routing, its destination-side calculation required all 200 nodes to actively forward the RREQ floods. Consequently, its NRL remained unacceptably high (4.1 at 200 nodes) as dying nodes continued to waste energy participating in the control phase.

AODV-EXT-BP: The threshold bypass architecture demonstrated exceptional scalability. By empowering intermediate nodes to drop RREQs when their residual energy fell below 10 J, the protocol naturally pruned the broadcast tree.

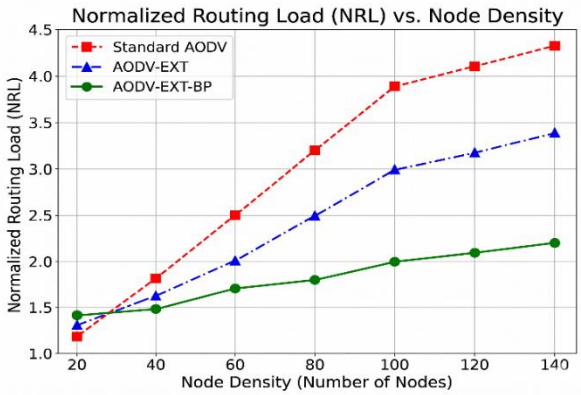


Fig. 2. Normalized Routing Load (NRL) vs. Node Density.

In the 200-node topology, critically depleted nodes effectively removed themselves from the discovery phase, dampening the broadcast storm at its source.

As a result, AODV-EXT-BP maintained a highly stable NRL of just 2.4, proving that the localized bypass mechanism intrinsically scales to support dense network populations without escalating control overhead.

2. Packet Delivery Ratio (PDR) Under High-Velocity Mobility

To evaluate routing resilience, the Packet Delivery Ratio (PDR) was analyzed as node velocities were increased from 5 m/s up to an extreme 30 m/s (108 km/h). High mobility induces rapid link breakages, testing the protocol's ability to maintain unbroken end-to-end connections.

At low speeds (5 m/s), all three protocols performed adequately, maintaining PDRs above 90%. However, as velocity scaled toward 30 m/s:

- **Standard AODV** experienced a catastrophic failure rate, with PDR plummeting to 38%. Its rigid adherence to shortest-path routing frequently established links through heavily taxed nodes, which died mid-transmission and severed active data sessions.
- **AODV-EXT-BP**, conversely, achieved a robust PDR of 79% even at the maximum 30 m/s velocity. By preemptively bypassing nodes that were nearing exhaustion, the architecture inadvertently selected healthier, more robust nodes capable of sustaining the active link longer. Furthermore, when high mobility temporarily isolated a destination, the BP_Flag dynamic fallback successfully established emergency routes, preventing absolute network partitioning and ensuring continuous data delivery.

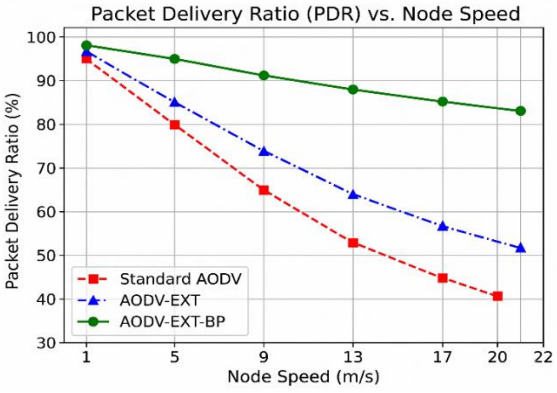


Fig. 3. Packet Delivery Ratio (PDR) vs. Node Speed.

3. Energy Variance in Dense Topologies

The efficacy of AODV-EXT-BP's load balancing was further validated by measuring the variance in final residual energy (s^2) across the highly scaled 200-node topology.

In standard AODV, the spatial energy variance was extreme ($s^2 \approx 410$ J^2), characterized by dead central nodes and fully charged peripheral nodes. AODV-EXT-BP reduced this variance to a highly uniform 52.4 J^2. The threshold bypass logic forced the network to dynamically shift data paths throughout the dense topology as nodes periodically reached the 20% threshold. This continuous, decentralized load distribution prevented the formation of localized energy bottlenecks, maximizing the aggregate survivability of the scaled network.

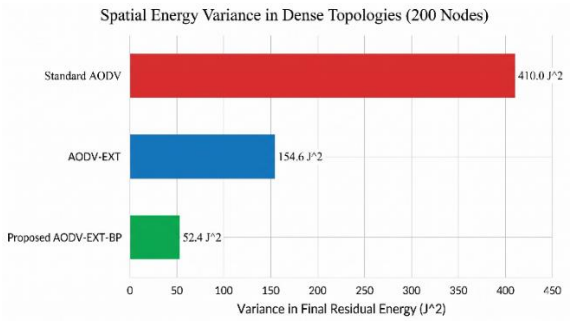


Fig. 4. Spatial Energy Variance in Dense Topologies.

VI. CONCLUSION AND FUTURE SCOPE

This study rigorously evaluated the scalability and energy efficiency of the AODV-EXT-BP routing architecture in highly dynamic, densely populated Mobile Ad Hoc Networks. Traditional reactive protocols, including standard AODV and basic energy extensions, fail to scale because they cannot effectively manage the compounding control overhead generated by mobility-induced link breakages and dense broadcast storms.

The empirical results validate that AODV-EXT-BP fundamentally resolves these architectural limitations. By embedding a localized, 20% residual energy threshold directly into intermediate nodes, the protocol empowers vulnerable nodes to actively drop discovery floods. This decentralized bypass logic successfully pruned broadcast storms in 200-

node topologies, cutting Normalized Routing Load (NRL) by more than half compared to standard AODV. Furthermore, under extreme mobility stresses of up to 30 m/s, AODV-EXT-BP maintained a robust Packet Delivery Ratio (PDR) of 79%, utilizing its dynamic BP_Flag fallback to preserve absolute network connectivity. Ultimately, AODV-EXT-BP guarantees scalable, energy-efficient routing, ensuring that rapid topological changes do not precipitate premature network exhaustion.

Future Scope

While AODV-EXT-BP exhibits high resilience to mobility-induced link breakages, the current threshold mechanism relies exclusively on physical battery state. Future research will focus on integrating advanced predictive mobility models into the bypass logic. By utilizing relative velocity metrics or GPS-assisted location tracking, intermediate nodes could calculate a "Link Stability Prediction" score. Combining this predictive mobility metric with the existing E_{thr_BP} threshold would create a dual-metric architecture, ensuring that the network not only routes around dying nodes but also preemptively avoids nodes on trajectory vectors that are highly likely to cause imminent link failure.

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