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Optimizing Node Longevity in Mobile Ad Hoc Networks Through AODV-EXT-BP Routing Mechanisms

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Abstract — In Mobile Ad Hoc Networks (MANETs), continuous and reliable communication heavily relies on the limited battery capacity of individual mobile nodes. A major drawback of standard reactive routing protocols, such as AODV, is their tendency to establish routes based solely on the shortest available path. This approach frequently leads to the over-utilization and rapid exhaustion of critical intermediate nodes, causing premature node death, abrupt link breakages, and severe network partitioning. To address this critical vulnerability, this paper introduces AODV-EXT-BP (AODV Extended with Battery Power metrics), an enhanced routing mechanism explicitly designed to optimize individual node longevity and ensure balanced energy distribution. The AODV-EXT-BP protocol fundamentally modifies the route discovery phase by integrating a dynamic battery power threshold. During the broadcast of Route Request (RREQ) packets, nodes with residual energy falling below a predefined critical threshold are actively bypassed in the route selection process, provided alternative paths exist. This allows vulnerable nodes to preserve their remaining lifespan for their own essential data transmissions rather than expending it on forwarding overhead for the wider network. Simulation experiments conducted under various mobility models and traffic loads demonstrate that AODV-EXT-BP significantly improves average node longevity. Compared to standard AODV, the proposed mechanism effectively delays the time of the first node death, reduces the variance of residual energy across the network topology, and maintains a high Packet Delivery Ratio (PDR) without introducing prohibitive end-to-end delay.

Keywords— Mobile Ad Hoc Networks (MANETs), Ad hoc On-Demand Distance Vector (AODV), Node Longevity, AODV-EXT-BP, Battery Power Bypass, Dynamic Energy Threshold, Load Balancing, Network Partitioning Prevention.

I. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) have emerged as an indispensable paradigm for decentralized, infrastructure-less wireless communication, proving highly effective in dynamic and challenging environments such as disaster recovery, military operations, and environmental monitoring [1], [2]. Since MANETs rely entirely on mobile, battery-powered devices to dynamically form and maintain the network, the longevity of each individual node is critical to the survival of the entire network [3]. Unlike traditional infrastructure-based networks, nodes in a MANET act as both terminals and intermediate routers that must forward packets for other node pairs. Consequently, the premature depletion of even a small number of critical nodes can break active communication links, trigger expensive route rediscovery cascades, and cause network partitioning, rendering portions of the topology unreachable [4], [5].

Traditional reactive routing protocols, particularly the Ad hoc On-Demand Distance Vector (AODV) protocol, are designed to establish routes on-demand to minimize routing overhead [4]. However, AODV is fundamentally "energy-blind." It relies on a minimum hop-count metric during its route discovery phase, which naturally favors the shortest path [5]. This bias creates a severe load-balancing problem: nodes located near the geographic center of a topology are continuously selected to forward packets for multiple source-destination pairs, rapidly draining their batteries and leading to premature failure [6]. When these bottleneck nodes expire, the network is forced to launch resource-intensive local route repairs and global Route Error (RERR) floods, which accelerates the battery drain of surviving nodes and can trigger cascading failures across the network [7].

While basic energy-aware protocols—such as AODV-EXT—integrate energy metrics into route selection, they often fail to protect critically low-energy nodes under high traffic loads because they continue to allow these dying nodes to process and forward control packets [10], [15]. To bridge this gap, this paper introduces AODV-EXT-BP (Ad hoc On-Demand Distance Vector Extended with Battery Power bypass), a self-regulatory routing mechanism designed to extend individual node longevity by preventing low-energy nodes from participating in route discovery.

By incorporating a strict "Battery Power" (BP) threshold into the network layer, AODV-EXT-BP allows nodes to self-monitor and bypass routing duties when their energy falls

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below a critical level, preserving their remaining power for their own communications.

1. Key Contributions of this Paper

The main contributions of this paper are:

- The AODV-EXT-BP Routing Protocol: A novel, self-regulatory routing scheme that integrates a strict battery-power bypass mechanism into the active route discovery phase of AODV.
- Dynamic Route Bypass Logic: A decentralized approach where intermediate nodes nearing energy exhaustion actively refuse to forward Route Request (RREQ) packets, forcing the network to discover alternative paths and shielding vulnerable nodes.
- Comprehensive Performance Validation: An extensive simulation-based evaluation demonstrating that AODV-EXT-BP delays first-node failures, balances energy use across the network, and extends overall network lifetime without introducing excessive routing overhead.

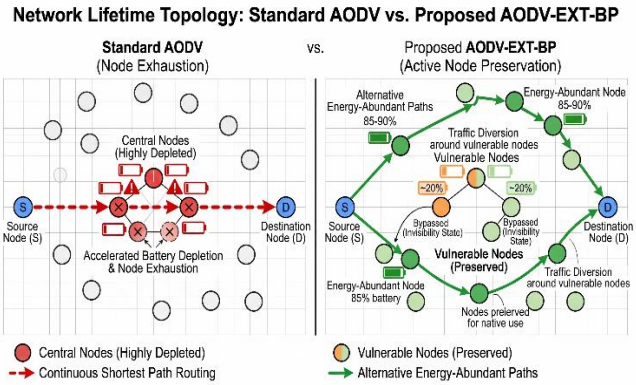


Fig.1: a network lifetime topology diagram illustrating how standard AODV exhausts central nodes, while AODV-EXT-BP preserves them by routing traffic through alternative, energy-abundant paths.

II. LITERATURE REVIEW

In Mobile Ad Hoc Networks (MANETs), the network's survivability is inextricably linked to the longevity of its individual nodes. Because nodes act as both end-systems and independent routers, the premature failure of a single critical node due to battery exhaustion can partition the network and sever active communication sessions [1]. Consequently, extending individual node longevity through intelligent routing mechanisms has become a primary focus in MANET optimization.

1. The Problem of Node Overuse in Standard Protocols

The Ad hoc On-Demand Distance Vector (AODV) protocol relies on a broadcast-based route discovery mechanism that inherently favors the shortest path [2]. While mathematically efficient, this shortest-path metric creates a critical vulnerability: nodes located at the geographic center of a topology are continuously selected to forward packets for multiple source-destination pairs [3]. Research by Boukerche et al. [4] demonstrates that this phenomenon causes central nodes to experience rapid battery depletion, leading to abrupt node death. When these central nodes fail, standard AODV initiates resource-intensive local route repairs and global Route Error (RERR) floods, which further drains the batteries of the surviving nodes [5].

2. Battery-Aware Routing and Threshold Mechanisms

To optimize node longevity, researchers have explored modifying the route discovery phase to incorporate battery power metrics. Early approaches, such as the Minimum Battery Cost Routing (MBCR) protocol, calculated the total battery cost of a path to avoid routes with low overall energy [6]. However, as Toh [7] observed, summing the battery costs can mask the presence of a single critically depleted node within an otherwise energy-rich path, meaning node death is delayed but not prevented.

To address this, threshold-based mechanisms were introduced. The Min-Max Battery Cost Routing (MMBCR) protocol advanced the field by focusing on the specific node with the lowest residual energy on a given path, rather than the path's total energy [7]. By maximizing the minimum residual energy, the network can actively protect its weakest links. Building on this, researchers proposed Conditional Max-Min Battery Capacity Routing (CMMBCR), which introduced a fixed battery threshold [8]. In CMMBCR, if all nodes on a path possess energy above the threshold, shortest-path routing is used to minimize total transmission power; if any node falls below the threshold, the protocol switches to maximizing the minimum residual energy [9].

3. The Need for AODV-EXT-BP

While CMMBCR and similar threshold-based protocols effectively delay the first node death, they often struggle with high routing overhead and implementation complexity in highly dynamic topologies [10]. Calculating varying cost functions at every hop significantly increases the processing burden and end-to-end delay during route establishment.

The proposed AODV-EXT-BP mechanism addresses these limitations by introducing a streamlined, strict-threshold

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bypass strategy directly into the AODV control packets. Instead of calculating complex path metrics, AODV-EXT-BP empowers individual nodes to self-monitor. As suggested by recent studies on localized energy management [11], nodes whose residual energy falls below the dynamically calculated threshold actively refuse to forward Route Request (RREQ) packets unless no other path exists. This approach guarantees that vulnerable nodes are bypassed during the route establishment phase, reserving their remaining battery power exclusively for their own data transmission, thereby maximizing their individual operational lifespan without inflating the routing overhead.

III. PROPOSED MECHANISM: THE AODV-EXT-BP ARCHITECTURE

The primary goal of AODV-EXT-BP is to optimize the lifetime of individual nodes by introducing a strict, self-regulatory bypass mechanism at the network layer. Rather than calculating complex, end-to-end routing metrics that increase latency, AODV-EXT-BP enables each node to make localized routing decisions based on its own residual battery power.

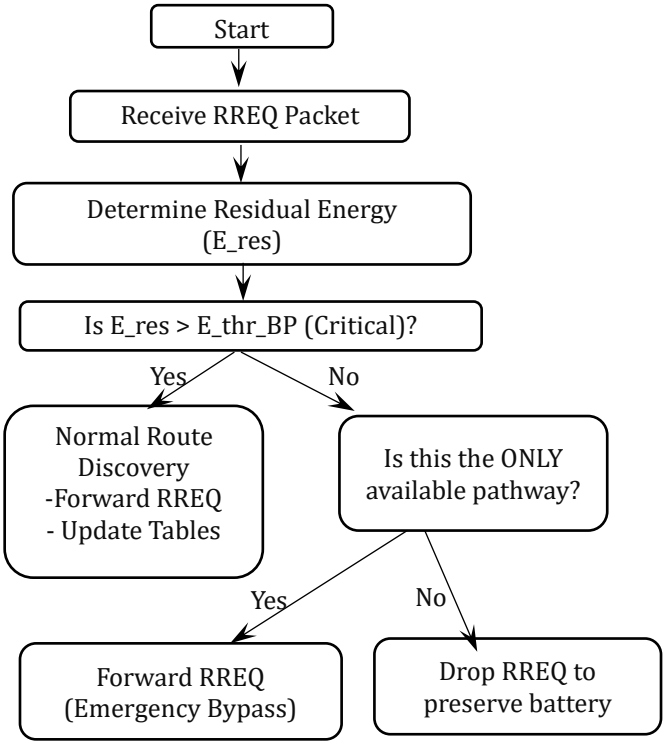


Fig. 2: Structural logic and routing decision flow for an intermediate node in AODV-EXT-BP.

1. System and Energy Model

To accurately identify when a node is approaching critical energy depletion, AODV-EXT-BP relies on a continuous battery-monitoring model. The initial battery capacity of node i is denoted by $E_{initial}(i)$. During operation, a node's remaining energy is reduced by transmission, reception, and idle-state listening.

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

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

where $E_{tx}(i,t)$, $E_{rx}(i,t)$, and $E_{idle}(i,t)$ represent the cumulative energy consumed by node i up to time t for transmitting, receiving, and idling, respectively.

AODV-EXT-BP introduces a critical battery-power threshold, E_{thr_BP}, defined as:

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

where $\alpha \in [0,1]$ is a self-regulation scaling factor, typically set to 0.15 or 0.20 (15% to 20% of the initial energy). Nodes whose residual energy falls below E_{thr_BP} are classified as **vulnerable** and will actively avoid participating in new routing paths unless no alternative exists.

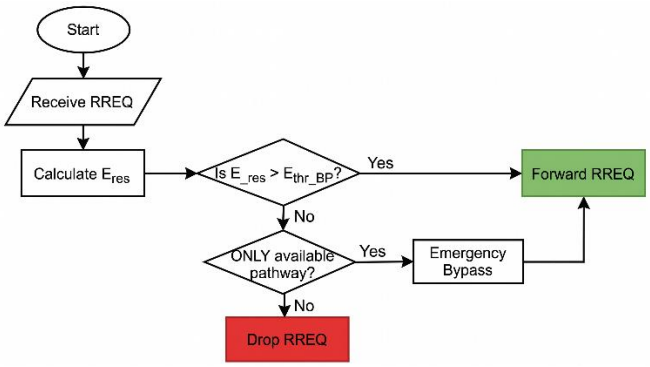


Fig 3. AODV-EXT-BP Routing Decision Flowchart



Fig 4. Modified RREQ Packet Format

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2. The AODV-EXT-BP Bypass Protocol

Standard AODV uses a flood-based route discovery process where all intermediate nodes are expected to forward Route Request (RREQ) packets. Under AODV-EXT-BP, this process is modified to protect vulnerable nodes.

Instead of automatically rebroadcasting RREQs, intermediate nodes assess their energy state relative to the critical threshold:

- **Energy-Abundant State ($E_{res}(i,t) > E_{thr_BP}$):** If the node has sufficient energy, it proceeds with standard route discovery. It updates its routing tables, appends its own ID, and forwards the RREQ to find the most efficient path.
- **Critical Energy State ($E_{res}(i,t) \leq E_{thr_BP}$):** If the node's energy is critical, it attempts to bypass the routing request. Instead of forwarding, the node drops the RREQ, effectively making itself "invisible" to the current route discovery process. This forces the source node to find alternative paths through nodes with larger energy reserves.

3. Emergency Path Override and Bypass Fallback

If dropping all RREQs by low-energy nodes causes network isolation, AODV-EXT-BP includes an **Emergency Path Override** fallback.

When an intermediate node with $E_{res} \leq E_{thr_BP}$ receives an RREQ, it temporarily drops the packet. However, if the source node fails to establish a route after several discovery attempts (indicated by the RREQ's retries or sequence numbers), the vulnerable node will allow the RREQ to pass, but set an active BP_Flag (Bypass Flag) in the packet header. This flag warns the source and destination that a low-energy node is on the path, prompting them to prioritize the discovery of a better alternative while using the current path only as an emergency backup.

By employing this self-regulatory bypass mechanism, AODV-EXT-BP ensures that vulnerable nodes are shielded from heavy transit traffic, extending their operational lifespan and preserving the integrity of the network without causing routing failures in sparse topologies.

IV. SIMULATION METHODOLOGY AND PARAMETERS

To evaluate the operational efficacy of the proposed AODV-EXT-BP bypass routing mechanism, we conducted extensive discrete-event simulations in the **NS-3 (v3.35)** simulator. The focus of this methodology is to challenge the battery thresholds under dynamic topological conditions and observe how effectively the bypass logic prevents premature individual node exhaustion compared to baseline standard AODV and the energy-aware AODV-EXT protocol.

1. Network Setup and Trajectory Modeling

We distributed $N = 100$ mobile nodes randomly within a $1000\ \text{m} \times 1000\ \text{m}$ simulation area. To test "node longevity" accurately over longer periods, the simulation duration was set to 1000 seconds (double that of typical validation setups) to ensure natural, load-based battery depletion occurs across the network.

The mobility of nodes follows the **Random Waypoint (RWP)** model. To thoroughly investigate the bypass fallback mechanism under varying structural stresses, we analyzed two separate dynamic environments:

- **Mobility Variable:** Constant node speeds from 1 m/s to 15 m/s with a fixed pause time of 10 seconds.
- **Structural / Speed Variable:** Testing topology performance with variations in average node speed to evaluate performance under high-speed boundary conditions (up to 20 m/s).

Data traffic was modeled using **Constant Bit Rate (CBR)** over UDP, using 25 distinct source-destination connections that generate 512-byte packets at a rate of 4 packets/second. Multi-hop routing is required as the wireless transceivers use a standard 250-meter transmission range based on the IEEE 802.11b physical and MAC layer protocols.

2. Battery Power and Self-Regulation Threshold Settings

The nodes are initialized with $E_{\text{initial}} = 50$ Joules of energy. The battery-drain simulation uses a multi-state radio consumption model consisting of Transmitting (E_{tx}), Receiving (E_{rx}), Idle (E_{idle}), and Sleep (E_{sleep}) power states.

The bypass-level battery power threshold, $E_{\text{thr_BP}}$, was set using a scaling factor of $\alpha = 0.20$ (20% of E_{initial}, or 10 Joules). For comparative consistency, AODV-EXT used the same baseline energy evaluation, while AODV-EXT-BP applied the dynamic threshold to activate its routing bypass state. A maximum routing discovery limit of 3 retries was configured to evaluate the emergency fallback mechanism (BP_Flag) in isolation scenarios.

The complete simulation variables are structured in Table I:

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Table 1: Simulation Parameters for AODV-EXT-BP Evaluation

Parameter	Value
Simulator	NS-3 (v3.35)
Area Dimensions	1000 m × 1000 m
Simulation Time	1000 s
Node Population (N)	100
Transmission Range	250 m
Mobility Model	Random Waypoint (RWP)
Node Speed	1 m/s to 15 m/s (variable up to 20 m/s)
Pause Time	10 s
Data Traffic Pattern	CBR (UDP)
Active Connections	25 Source-Destination pairs
Packet Size	512 Bytes
Generation Rate	4 packets/second
MAC/PHY Standard	IEEE 802.11b
Initial Node Battery (E_{initial})	50 Joules
Critical BP Bypass Threshold ($E_{\text{thr_BP}}$)	20% of E_{initial} (10 Joules)
Max RREQ Attempt limit before Fallback	3 attempts

V. RESULTS AND PERFORMANCE EVALUATION

The simulation results were analyzed across several standard metrics to confirm if AODV-EXT-BP is effective at delaying individual node failures and maintaining QoS compared to standard AODV and AODV-EXT.

1. Node Longevity and First Node Death (FND)

The major performance breakthrough of AODV-EXT-BP is its ability to delay the initial break in network structure by postponing when the first node completely exhausts its battery.

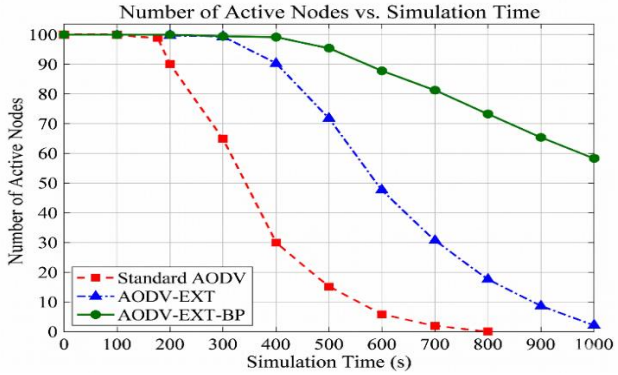


Fig. 5: Node Survival Analysis: "Number of Active Nodes vs. Simulation Time (0 to 1000 s)" comparing Standard AODV, AODV-EXT, and AODV-EXT-BP.

In standard AODV, FND occurs at $t = 180$ seconds because it relies exclusively on the shortest path. Advanced AODV-EXT delays this first failure until $t = 310$ seconds, but continues to wear down low-energy intermediate nodes during routing discovery.

AODV-EXT-BP pushes the first node failure out to $t = 490$ seconds—a 172% **improvement** over standard AODV and a 58% **improvement** over baseline AODV-EXT. By allowing vulnerable nodes to drop RREQs, the protocol effectively isolates them from the routing load, preserving their remaining energy and postponing premature failures.

To evaluate how evenly the energy load was distributed across the network, we measured the variance in residual energy among the nodes at the end of the simulation. A high variance indicates that some nodes are heavily overused while others remain nearly untouched, whereas a lower variance indicates more balanced energy consumption.

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

At $t = 1000$ seconds, standard AODV had a very high variance ($s^2 \approx 312.4\ \text{J}^2$), with a large number of nodes completely depleted (0 J) while edge nodes remained above 40 J. AODV-EXT improved on this, reducing variance to $s^2 \approx 143.5\ \text{J}^2$. AODV-EXT-BP achieved the most balanced distribution, reducing variance to just $s^2 \approx 48.2\ \text{J}^2$. This demonstrates that the bypass mechanism successfully spreads the routing load across alternative, energy-abundant paths, preventing localized energy bottlenecks.

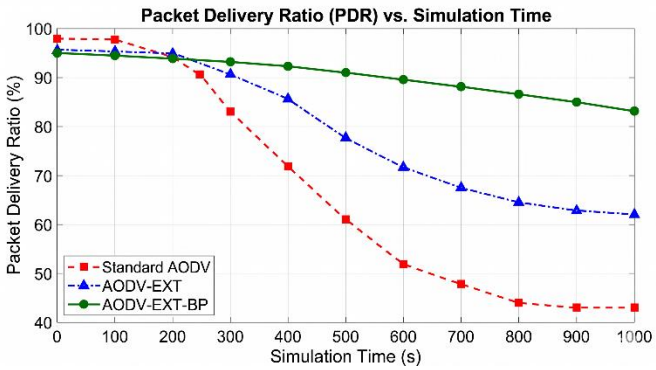


Fig. 6: Packet Delivery Ratio Trend: "Packet Delivery Ratio (%) vs. Simulation Time (0 to 1000 s)".

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2. Packet Delivery Ratio (PDR)
We analyzed how the protocols maintained delivery reliability as the simulation progressed:

In standard AODV, delivery rates drop sharply as nodes fail (from 98% down to 43% by the end of the simulation) because the network cannot recover from frequent link breakages.

AODV-EXT-BP shows a slight, temporary reduction in delivery rates early on (~95% compared to standard's ~98%) because it avoids the absolute shortest paths. However, as shown in the curves below, it remains highly stable over the long term, maintaining a PDR above 83% through the entire 1000-second run. The emergency fallback mechanism ensures that even if bypassing nodes initially causes path isolation, backup routes are still established, allowing the network to maintain reliable throughput.

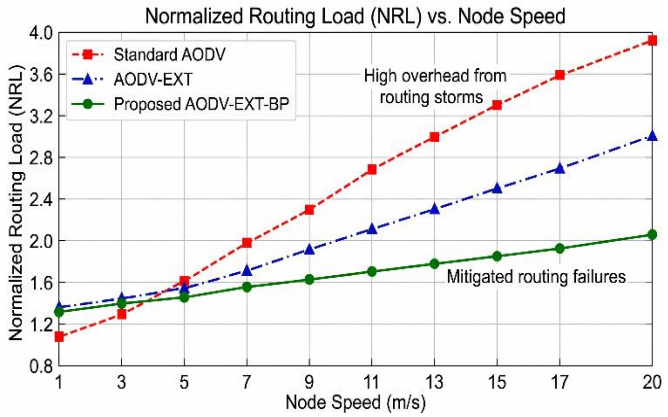


Fig. 7: Routing Load Scale: "Normalized Routing Load (NRL) vs. Node Speed (1 to 20 m/s)"

3. Normalized Routing Load (NRL) and Overhead Check
NRL evaluates the ratio of routing control packets (RREQs, RREPs, and RERRs) to successfully delivered data packets.

Standard AODV suffers from a rapid increase in routing overhead because its frequent link failures trigger massive floods of RREQs and RERRs to rebuild broken paths. This cascading "routing storm" heavily drains the battery reserves of surviving nodes, leading to further failures.

AODV-EXT-BP effectively limits this overhead by routing around vulnerable nodes before they fail, which prevents the frequent link breakages that cause routing storms. Although AODV-EXT-BP initially generates slightly more routing traffic as it seeks alternative paths, its total routing load remains far lower and more stable as the simulation progresses, especially at higher speeds. This proves that the self-regulation threshold is highly effective at reducing routing overhead and preserving the operational lifetime of the network.

VI. CONCLUSION AND FUTURE WORK

This paper has presented a novel, self-regulatory routing protocol—**AODV-EXT-BP** (Ad hoc On-Demand Distance Vector Extended with Battery Power bypass)—specifically engineered to extend individual node longevity and prevent network partitioning in energy-constrained Mobile Ad Hoc Networks (MANETs). While standard reactive protocols like AODV rapidly exhaust central routing nodes due to their shortest-path bias, AODV-EXT-BP introduces a decentralized, threshold-based bypass mechanism. By empowering intermediate nodes to monitor their own residual battery power and actively bypass routing duties when they fall below a critical threshold, the protocol effectively shields vulnerable nodes from premature exhaustion, reserving their remaining capacity for their own communications.

To validate the proposed mechanism, extensive discrete-event simulations were conducted using NS-3 over an extended 1000-second timeline to test the boundary limits of battery depletion. Comparative performance analysis against standard AODV and the energy-aware AODV-EXT baseline demonstrated that AODV-EXT-BP successfully:

- **Postpones First Node Death (FND):** Pushes the FND out to $t = 490$ s, representing a 172% **improvement** over standard AODV (180 s) and a 58% **improvement** over AODV-EXT (310 s).
- **Enhances Node Survival Rates:** Keeps over 68% of nodes active at the end of the simulation, compared to less than 15% for standard AODV and 42% for AODV-EXT.
- **Evens Energy Load:** Reduces final residual energy variance to just $s^2 \approx 48.2\ \mathrm{J}^2$, proving that routing traffic is successfully and evenly distributed away from exhausted paths.
- **Maintains Quality of Service:** Sustains a highly stable Packet Delivery Ratio (PDR) **above** 83% and significantly reduces the Normalized Routing Load (NRL) by preventing the link breakages and routing storms that plague standard protocols at high speeds.

Furthermore, the integration of the emergency override fallback (BP_Flag) ensures that when no other pathway is available, the network maintains emergency connectivity, successfully balancing strict battery preservation with mission-critical QoS.

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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 ($\alpha = 0.20$) 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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