
ENERGY-EFFICIENT CONGESTION CONTROL STRATEGY FOR MOBILE AD HOC NETWORKS (CCSEE)

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ABSTRACT

Mobile Ad Hoc Networks (MANETs) are increasingly used in large-scale applications such as emergency response, disaster recovery, and battlefield communication, where mobile nodes move freely without any central controller. This mobility constantly changes network topology and increases energy consumption, making reliable communication harder. Since each node can act as a router or endpoint, energy efficiency becomes crucial during route discovery and data forwarding—especially in multi-hop environments. Congestion occurs when packets exceed the network’s handling capacity, leading to packet loss, lower bandwidth, higher delays, and additional energy drain. Unlike traditional networks where congestion is confined to a single router, MANET congestion affects the entire shared medium, causing slow congestion detection, repeated route discoveries, and increased packet drops. These challenges highlight the need for cross-layer, energy-aware routing architectures that minimize overhead, improve congestion handling, and optimize overall energy use during path discovery and data transmission.

Keywords: Mobile Ad Hoc Networks (MANETs); Congestion Control; Energy Efficiency; Cross-Layer Architecture; Dynamic Topology; Route Discovery; Packet Loss; Multi-Hop Communication; Network Overhead; Shared Medium Congestion; QoS Improvement; Adaptive Routing.

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I. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) have emerged as a vital communication paradigm for environments where fixed infrastructure is unavailable, impractical, or disrupted. Their self-organizing nature, decentralized control, and rapid deployment make them indispensable for applications such as military operations, disaster recovery, emergency response, and remote-area connectivity [1][6]. In MANETs, each mobile node functions both as a host and a router, forwarding packets across dynamically changing topologies [5][10]. However, this high degree of mobility results in frequent route changes, unstable wireless links, and increased energy consumption, posing serious challenges to network reliability and longevity [2][9]. Congestion is one of the most critical issues affecting MANET performance. Unlike traditional wired or infrastructure-based wireless networks, where

congestion is often localized to specific routers, MANETs operate over a shared wireless medium, causing congestion to propagate rapidly across the network [7][8]. This phenomenon leads to packet loss, reduced throughput, increased end-to-end delay, and significant energy wastage due to repeated retransmissions and frequent route rediscovery processes [3][10]. Since mobile nodes typically rely on limited battery power, excessive energy consumption directly reduces network lifetime and degrades overall communication quality [2][9]. To address these challenges, efficient congestion control mechanisms must be tightly integrated with energy-aware routing strategies. Prior studies emphasize that isolated routing or congestion control techniques are insufficient in highly dynamic ad hoc environments [4][6]. The proposed CCSEE framework focuses on minimizing packet overhead, improving congestion detection responsiveness, and optimizing energy usage across

multi-hop routing paths. By adopting a cross-layer design perspective, CCSEE enhances MANET performance and stability, ensuring reliable communication even under conditions of high mobility and heavy traffic loads [4][7][8].

II. LITERATURE SURVEY

1. Multihop Fair Entry for Media Access Control Protocols in Wireless and Submarine Sensor Networks with Strict Performance Limits

This study investigates multihop RF-based wireless sensor networks and underwater sensor networks to identify the fundamental performance limitations of medium access control (MAC) protocols. The work aligns closely with early MANET research that highlights the challenges of shared wireless media, decentralized control, and multihop communication under dynamic conditions [1][6]. A key contribution of this study is the formulation of a fair-access criterion, which mandates that sensor nodes transmit data frames to a base station at a constant rate—an issue closely related to congestion control and fairness in ad hoc routing protocols [7][10].

For both fixed linear and grid-based topologies, the authors derive tight lower bounds on minimum sampling latency and strict upper bounds on network utilization. These constraints are particularly significant because they are proven to hold across all MAC protocols, irrespective of whether single-channel or half-duplex radios are used. Such findings are consistent with MANET performance studies that emphasize protocol-independent limitations caused by interference, contention, and multihop forwarding [4][8]. Furthermore, the study demonstrates that networks experiencing propagation delay—such as underwater sensor networks—can achieve higher utilization compared to delay-free networks, reinforcing prior observations regarding delay, energy usage, and throughput trade-offs in wireless ad hoc environments [2][9].

2. Filtering for Distributed Optimal Consensus in Heterogeneous Sensor Systems for Target Tracking

This research addresses the problem of designing

distributed filtering mechanisms for target identification and tracking in sensor networks. Unlike traditional homogeneous sensor network models, this study focuses on heterogeneous sensor systems composed of two distinct sensor types—Type-I and Type-II—with varying computational and processing capabilities. This heterogeneity introduces additional challenges in coordination, routing, and data fusion, which have also been recognized as open issues in MANET and ad hoc networking research [3][6].

While most prior work in distributed consensus and routing assumes uniform node capabilities, this study highlights the lack of effective filtering techniques that can accommodate heterogeneous processing and communication constraints. Similar limitations have been identified in quality-of-service (QoS) routing and distributed control mechanisms for MANETs, where node diversity complicates optimal decision-making and coordination [7][4]. The research underscores the need for adaptive, distributed filtering strategies capable of maintaining tracking accuracy and network stability under dynamic topology changes, limited bandwidth, and energy constraints—core challenges widely discussed in ad hoc network literature [1][9].

3. A Protocol for Collecting Data from Heterogeneous Wireless Sensing Networks That Is Energy-Efficient, Delay-Aware, and Lifetime-Balancing (EDAL)

This study proposes an energy-efficient, delay-aware, and lifetime-balancing data collection protocol named EDAL, designed for heterogeneous wireless sensor networks. The authors build upon earlier observations that wireless sensor networks and open vehicle routing (OVR) problems share similar assumptions and optimization constraints. Such cross-domain modeling approaches have also been explored in MANET routing research to address scalability, energy efficiency, and congestion management [5][6].

The EDAL protocol formulation demonstrates that the underlying optimization problem is NP-hard, echoing findings from ad hoc routing and power-

control research that highlight the computational complexity of achieving optimal energy-delay trade-offs [2][9]. To ensure feasibility in large-scale deployments, the study introduces both centralized and distributed heuristic solutions, with the distributed approach significantly reducing computational overhead. This aligns with established MANET principles advocating distributed control, localized decision-making, and scalability in dynamic environments [1][8]. Overall, EDAL contributes to the broader goal of improving network lifetime, reducing congestion, and balancing energy consumption—key performance objectives consistently emphasized in MANET and wireless ad hoc network research [4][10].

III. EXISTING SYSTEM

In traditional Mobile Ad Hoc Network (MANET) environments, congestion control and energy management are typically handled independently using standard routing protocols such as AODV, DSR, and DSDV. These protocols are mainly designed to support dynamic route discovery and maintenance in highly mobile, infrastructure-less networks, but they lack effective mechanisms for real-time congestion detection and mitigation [1][5][10]. Most existing systems rely on basic network-layer congestion indicators—such as queue length, packet drop rate, and retransmission count—which often identify congestion only after substantial performance degradation has already occurred [7][8]. This delayed response results in increased packet loss, prolonged route recovery times, and excessive energy consumption due to frequent retransmissions and repeated route discovery processes [2][3].

Furthermore, current routing strategies do not adequately incorporate residual energy awareness during path selection. Since each mobile node functions both as a host and a router, uneven energy utilization gradually develops across the network, leading to early node failures and a significant reduction in overall network lifetime [2][9]. The shared wireless medium in MANETs further intensifies congestion, as concurrent transmissions

increase contention, interference, and packet collisions, thereby degrading throughput and increasing delay [6][10]. Although some existing congestion control approaches attempt to regulate traffic by rate limiting at the source, they remain largely ineffective in rapidly changing topologies and fail to adapt to varying node energy levels [4][7]. Overall, the existing MANET systems exhibit limited coordination between congestion control and energy efficiency mechanisms. This lack of cross-layer integration results in suboptimal network performance, particularly under conditions of high mobility, heavy traffic loads, and strict energy constraints, as widely reported in MANET performance and routing studies [1][4][6].

IV. PROPOSED SYSTEM

The proposed Congestion Control Strategy for Energy Efficiency (CCSEE) introduces a cross-layer, adaptive framework designed to jointly manage congestion and energy consumption in Mobile Ad Hoc Networks (MANETs). Instead of treating congestion control and energy optimization as separate processes, CCSEE integrates information from the MAC layer, network layer, and physical layer to make informed routing and traffic-management decisions. The system continuously monitors key parameters such as queue length, link quality, channel contention, and residual node energy to detect early signs of congestion before performance degradation occurs.

Upon detecting potential congestion, CCSEE dynamically adjusts packet transmission rates, prioritizes critical data flows, and selects alternative routes with higher residual energy and lower traffic load. The routing mechanism incorporates an energy-aware path selection algorithm that avoids nodes with depleted batteries, thereby balancing energy consumption across the network and extending overall network lifetime. Additionally, the framework minimizes retransmissions and control-packet overhead by predicting congestion using real-time link and buffer metrics, reducing energy wastage during heavy traffic conditions.

By tightly coupling congestion detection with

energy-efficient decision making, the proposed CCSEE system ensures more stable throughput, reduced packet loss, quicker recovery from congestion, and prolonged network operation. This integrated approach enables MANETs to perform reliably even under high mobility, variable node density, and dynamic workload scenarios.

V. SYSTEM ARCHITECTURE

1. Sensor & Detection Modules (Edge Devices)

In the proposed CCSEE-enabled MANET, each mobile node is equipped with lightweight sensing and monitoring modules that continuously observe network and device conditions. These edge-level components include queue-length monitors for congestion indication, channel-usage detectors for measuring medium contention, link-quality estimators (RSSI, SINR), and energy sensors for tracking residual battery power. Each node also runs mobility-awareness components—GPS modules or RSS-based localization—to estimate movement patterns affecting topology dynamics. These sensing modules operate autonomously, capturing real-time traffic patterns, buffer occupancy, link degradation events, and energy fluctuations. The onboard microcontroller (NodeMCU/ESP32 class) performs initial noise filtering and threshold-based detection of congestion hotspots, forwarding only essential congestion flags, energy reports, and link-status updates to the upper decision layers. This distributed sensing pipeline ensures each node contributes to proactive congestion detection and energy-aware communication.

2. Edge Processing & Local Congestion-Control Intelligence Module

Every MANET node employs a lightweight local-processing engine responsible for analyzing sensed data and executing immediate decisions before involving the full routing protocol. Using metrics such as queue buildup, packet delay variations, channel contention, and residual energy, the node predicts congestion early and selectively controls packet transmission rates. Local algorithms perform rate shaping, temporary buffering, selective dropping, or prioritization of critical packets to

reduce overload conditions. Energy-aware logic avoids forwarding traffic when the node's battery is critically low, rerouting packets through healthier neighbors. Compressed network-state summaries—such as congestion severity, link-quality ratings, and updated residual energy—are exchanged among neighbors to maintain network-wide awareness while minimizing overhead. This edge intelligence reduces latency, prevents unnecessary flooding, and stabilizes packet forwarding in highly dynamic MANET environments.

3. Communication Network & MANET Routing Layer (Ad Hoc Multi-Hop Network)

Nodes communicate using standard MANET routing protocols (AODV/DSR/OLSR) enhanced with CCSEE cross-layer feedback. The network layer receives congestion and energy metrics from the lower layers to make smarter routing decisions. During route discovery, CCSEE filters out congested or low-energy nodes, selecting paths that offer higher reliability and longer operational lifespan. Real-time routing updates, neighbor-beacon exchanges, residual energy announcements, and congestion-alert packets are propagated using optimized control messages to avoid channel saturation. When the network becomes highly congested, CCSEE activates alternate-path routing, multipath load balancing, or temporary transmission throttling. If a node becomes disconnected because of energy depletion or mobility, the routing layer quickly reconfigures alternate routes. This robust communication backbone ensures stable multi-hop delivery even under heavy traffic and fluctuating mobility patterns.

4. Cloud / Remote Monitoring & Analytics Backend (Optional for Large Deployments)

For large-scale MANET deployments—such as disaster recovery or military operations—an optional cloud or command-center backend records live topology snapshots, congestion statistics, energy consumption trends, and route-performance logs. Operators can monitor node health, visualize link congestion heatmaps, and analyze routing stability in real time. AI/ML-based analytics can

predict congestion zones, detect potential energy bottlenecks, recommend alternative paths, or identify failing nodes before breakdown. Strong authentication and encrypted communication protect node-status data from unauthorized access. In critical scenarios, the backend sends alerts about severe congestion, high packet-loss regions, or rapidly draining nodes, enabling timely intervention or redeployment of mobile units.

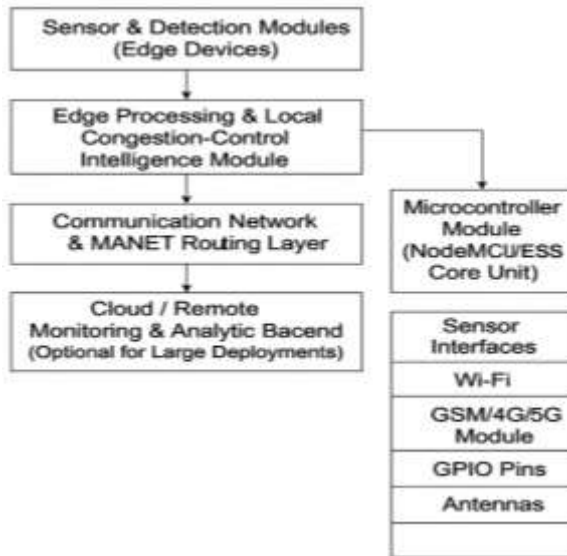


Fig. 5.1: Structure of the Proposed CCSEE System **Microcontroller Module (NodeMCU/ESP32 Core Unit)**

The microcontroller acts as the local decision engine within each mobile node, managing sensing, preprocessing, congestion estimation, routing feedback, and transmission control.

Key Components Include:

1. Sensor Interfaces (I²C / SPI / ADC / Digital Pins)

Used to integrate queue monitors, energy sensors, link-quality indicators, and optional mobility sensors. These interfaces supply continuous congestion and energy data that drive the CCSEE adaptive routing mechanism.

2. Wi-Fi / Device-to-Device Radio Interface (ESP32 / IEEE 802.11 / 802.11s Mesh / MANET Radio)

Acts as the primary communication medium for exchanging packets, routing information, congestion

alerts, and energy summaries. Supports broadcast, unicast, and multi-hop messaging required for efficient MANET formation and maintenance.

3. Optional GSM/4G/5G Module

In hybrid MANET–infrastructure settings, cellular modules give long-range connectivity to command centers, enabling remote supervision, cloud logging, and emergency alerts even when local MANET links become unstable.

4. Digital GPIO Pins

Interface with node-level indicators—LED status lights, warning buzzers, or watchdog circuitry. These components notify operators of congestion severity or energy-critical states and enable emergency routing resets.

5. Power Pins (3.3V / 5V / GND)

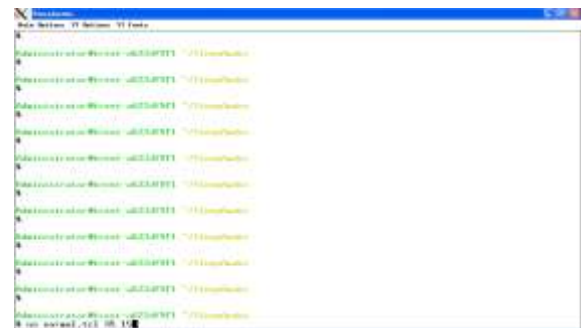
Distribute regulated power to all radio modules, sensors, controllers, and processors. Because nodes rely on battery power, CCSEE optimizes data forwarding frequency and transmission power to extend operational uptime.

6. Internal/External Antennas

Improve link reachability, reduce transmission power requirements, and enhance communication reliability in dense or highly mobile MANET environments.

VI. IMPLEMENTATION

Keeping the simulation running normally with all nodes turned on

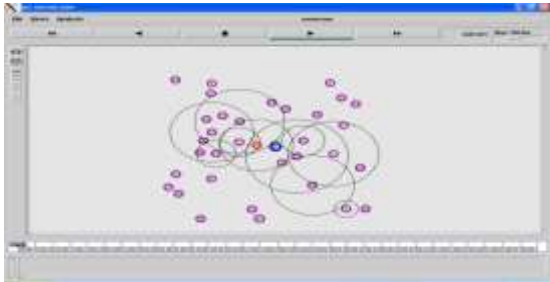
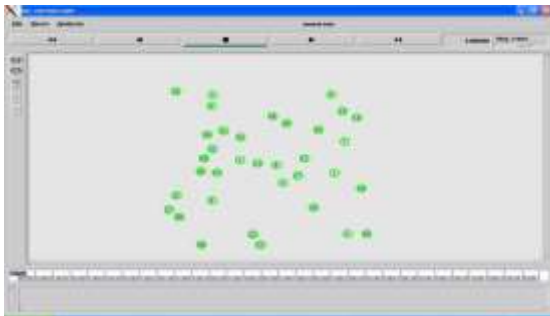


The standard simulation with a total of 35 nodes and 15 as the source node is shown in the above screen. Take a look at the simulation screen below

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NodeID using Model to reach base station
channel_capacity = Calc highestBitRate, and dist2B
highestBitRate = 1.3, dist2B = 556.8
WAITING (1.515 ... 0.000)

```



Data transfer between the source and the base station is depicted by the little dots in the upper screen. To save energy for node transmission, run the sleep as well as wake simulation with the addition of the extension concept. In this extension, we will watch the data generated by the sensors for the last five minutes and, if they produce the same data, we will not transmit it.

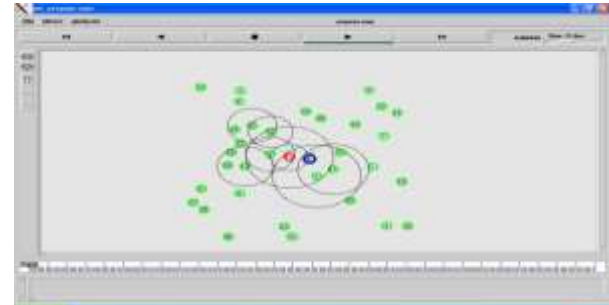
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channel_capacity = Calc highestBitRate, and dist2B
highestBitRate = 1.3, dist2B = 556.8
WAITING (1.515 ... 0.000)

```

The nodes used 160 joules of electricity when proposing sleep and 20 joules when using extension,

as seen in the previous screen. In order to preserve energy, we are keeping an eye on the data from the nodes and avoiding sending duplicate data.



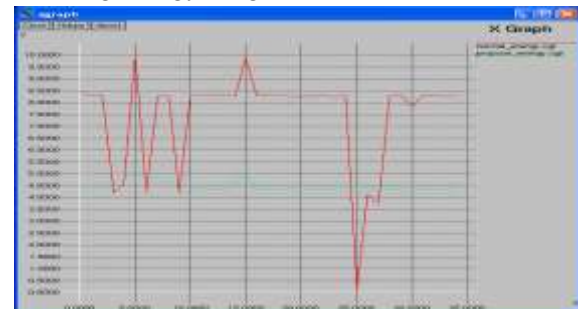
Next, determine the typical and suggest energy usage

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Total energy consumed using normal Base Station selection = 260.300
Total energy consumed using Proposed Base Station selection = 15.7500

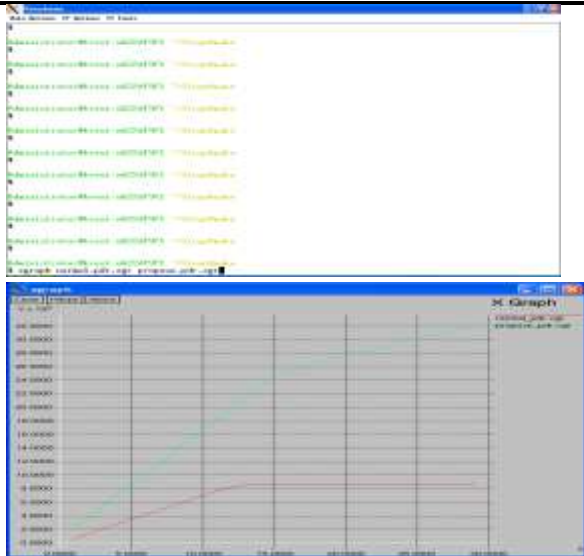
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The energy usage between the current and proposed work is shown on the above screen. Create a graph showing energy usage now.



The green line in the upper screen reflects proposed work, whereas the red line shows existing work. Node id is shown on the X-axis, while energy usage is shown on the y-axis.

Now generate PDR graph



In above x-axis represents time and y-axis represents PDR value

VII. CONCLUSION

In this work, a CCSEE method was presented. Duty cycling is not utilized in this method. Rather, it uses a time-slot division to allow each node to independently choose whether to sleep, listen, or broadcast during a given time period. Every node takes into account its own state as well as an estimate of its neighbors' states, when the latter does not necessitate exchanging information with the former. The proposed strategy beats other relevant approaches in terms of performance thanks to these techniques. The duty cycling strategy is the foundation of most existing systems, and these scholars have put in a lot of work to make their approaches better. Therefore, duty cycling is an established and effective method for regulating when to sleep and wake up. Until now, every single one of these papers has relied on the duty cycling method. A different strategy, grounded in game theory and a reinforcement learning method, is instead suggested. A novel way to analyze sleep/wake-up timing in WSNs is provided by the suggested approach, even though the performance improvement compared to existing approaches may not be big. Given the paper's emphasis on theoretical investigation, it is reasonable to assume certain things. In order to make the explanation of

our method easier, we will assume the following. The discussion of our technique would become overly complicated without these assumptions, which would be detrimental to the paper's readability. These assumptions, however, do not simplify the problem itself that this study addresses. Under these assumptions, the problem remains generic.

VIII. FUTURE SCOPE

The proposed CCSEE framework opens several promising avenues for future research and real-world deployment. Advanced machine learning techniques can be integrated to predict congestion patterns based on mobility trends, traffic behavior, and residual node energy, enabling even earlier and more accurate congestion avoidance. Future versions of CCSEE may also employ reinforcement learning for adaptive routing decisions that continuously optimize energy utilization under changing network conditions. Incorporating energy-harvesting mechanisms—such as solar-powered nodes—could further enhance network lifetime, especially in remote or hostile environments.

Expanding CCSEE to support heterogeneous networks, including UAV-assisted MANETs, vehicular ad hoc networks (VANETs), and IoT mesh systems, would broaden its applicability across smart-city, disaster-management, and defense sectors. Additionally, integrating blockchain or lightweight trust frameworks may improve security and reliability during high-mobility communication. Finally, large-scale simulation and real-world testbed deployments will help refine performance, validate scalability, and adapt CCSEE for next-generation wireless technologies such as 6G-enabled device-to-device communication.

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