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Performance Evaluation of the d-Hop Clustering Algorithm in Mobile Ad Hoc Networks

CENG 797 Ad Hoc Networks
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Term Project Report

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1 Introduction

1.1 The Challenge of Maintaining Stable d-Hop Clusters in MANETs

Mobile Ad Hoc Networks (MANETs) rely on decentralized, self-configuring nodes that communicate over wireless links without fixed infrastructure. The absence of centralized control means that each node must independently manage routing, security, and resource allocation [2]. A key challenge in MANETs is maintaining efficient and stable clustering as the network size and mobility increase. This challenge is further compounded by dynamic topologies, where nodes frequently join or leave the network, requiring adaptive clustering algorithms [3]. Among various clustering approaches, the d-Hop algorithm offers a balance between cluster stability and scalability, making it suitable for evaluation under diverse MANET conditions.

1.2 Practical Importance of Efficient d-Hop Cluster Formation

Clustering—the grouping of nodes into clusters with designated cluster heads—is essential to improving MANET performance because it provides structural organization and supports scalable network management [4, 5]. An efficient clustering algorithm facilitates the formation of desirable and well-organized MANET topologies, enhancing network efficiency, reducing routing overhead, and improving overall communication performance [6]. Conversely, failing to address the clustering problem can result in inefficient and unstable network structures, leading to excessive overhead, uneven load distribution, and frequent topology disruptions. Therefore, solving this problem is a critical step toward achieving optimized, reliable, and sustainable MANET-based communication systems [7].

However, forming and maintaining stable clusters in MANETs is challenging due to node mobility, dynamic topologies, and decentralized control [8]. Simpler approaches, such as 1-hop, often fail to adjust to variations in network density or movement patterns [9]. In other words, they lack the adaptability required for the inherently dynamic nature of MANETs.

1.3 Objective: Assessing d-Hop Cluster Performance

This study aims to evaluate the performance of the d-Hop Clustering Algorithm in MANETs under varying network topologies, mobility patterns, traffic conditions, and energy constraints. Using OMNeT++ 6.2.0 and INET 4.5.4, the study will simulate network scenarios and measure the algorithm's effectiveness across cluster quality, overhead, communication efficiency, energy/resource usage, scalability, robustness, and fairness metrics.

1.4 Hypothesis: Stability and Efficiency Through d-Hop Clustering

It is hypothesized that the d-Hop Clustering Algorithm can maintain stable and efficient clusters across a wide range of network conditions, resulting in reduced control overhead, balanced energy consumption, and improved network performance compared to unclustered or poorly clustered MANETs.

1.5 Key Definitions for MANET Clustering Evaluation

- **MANET:** A self-configuring network of mobile nodes communicating without fixed infrastructure.

- **Clustering:** Grouping nodes into clusters with a cluster head to improve network management and performance.
- **d-Hop Clustering Algorithm:** A clustering method where nodes within d hops form a cluster, with one node elected as the cluster head.
- **Cluster Head (CH):** A node responsible for intra-cluster coordination and inter-cluster communication.
- **Metrics:** Quantitative measures of network performance, including cluster quality, communication efficiency, energy usage, scalability, and fairness.

By systematically analyzing these metrics, this study will provide a comprehensive assessment of the d-Hop Clustering Algorithm's suitability for dynamic and large-scale MANET environments.

2 Background and Related Work

2.1 Background

MANETs are decentralized, infrastructure-less systems in which mobile nodes communicate through multi-hop wireless links without relying on fixed base stations or routers. Each node acts both as a host and a router, forwarding packets for others to maintain end-to-end connectivity [2]. Due to node mobility, wireless interference, and limited energy resources, MANETs experience frequent topology changes that make routing, scalability, and energy management particularly challenging [3].

Clustering has emerged as an effective mechanism to address these challenges by partitioning the network into manageable groups of nodes, known as clusters [4, 5]. Each cluster is coordinated by a Cluster Head (CH), which is responsible for intra-cluster communication—the exchange of data and control messages *within* the cluster among its member nodes. Inter-cluster communication, on the other hand, refers to the communication *between* different clusters, typically facilitated by gateway nodes that act as bridges between cluster heads. Clustering enhances scalability, reduces routing overhead, supports efficient resource allocation, and improves overall energy efficiency by organizing communication hierarchically [6]. However, maintaining stable clusters under mobility and varying network densities remains an open research problem.

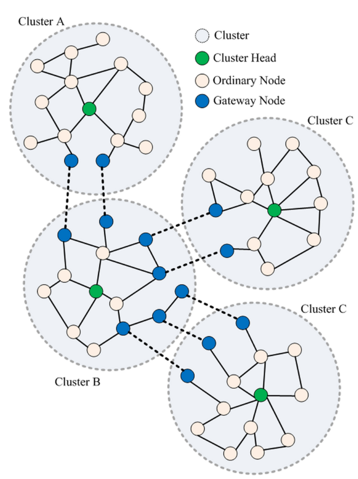

Figure 1 . Clustered Network Topology with Gateways [1].

To overcome these challenges, various clustering algorithms have been proposed, including Lowest-ID, Highest-Degree, and Weighted Clustering Algorithm (WCA) methods. While these approaches improve organization and connectivity, they often struggle with scalability as node density increases [10]. To address these limitations, multi-hop clustering strategies have gained attention for enhancing communication efficiency, network longevity, and load balancing, often combined with optimization, machine learning, and trust-based mechanisms to further improve energy efficiency and stability [11, 12, 13].

The d-Hop Clustering Algorithm represents a significant advancement in MANET clustering. Unlike 1-hop clustering, where clusters are formed based on immediate neighbors, d-hop clustering allows nodes within d hops to form a cluster, with one node elected as the cluster head [14]. This approach balances cluster stability and scalability, making it suitable for dynamic and large-scale MANET environments.

The reviewed studies highlight continuous efforts to enhance the stability and scalability of d-hop clustering through mobility-awareness and adaptive cluster sizing.

2.2 Related Work

1. **Max-Min D-Cluster (foundational formal model):** Introduced by Amis et al. at INFOCOM 2000, this algorithm is a widely cited, efficient heuristic for forming d-hop clusters in distributed networks. It establishes a formal framework for clusterhead election, ensuring all nodes are within d hops of a clusterhead while balancing clusterhead selection. The approach serves as a baseline for both theoretical extensions and practical comparisons in d-hop clustering research [14].
2. **Mobility-aware metrics and their adoption:** Basu et al. introduced a relative mobility metric derived from successive received signal strength (RSS) measurements between neighboring nodes. This metric quantifies pairwise mobility and was later integrated into mobility-based d-hop clustering algorithms. The core principle is to prioritize nodes with lower relative mobility as clusterheads, enhancing overall cluster stability. This mobility-centric approach became a foundational element in subsequent mobility-sensitive clustering designs and analyses [15].
3. **MobDHop: adaptive d-hop clustering based on mobility:** Er and Seah introduced MobDHop, an algorithm that integrates d-hop clustering with Basu's mobility metric to create variable-diameter clusters. By adapting cluster formation to local mobility conditions, MobDHop enhances stability and minimizes reconfiguration overhead. This work highlights the potential of dynamically adjusting the d-hop diameter parameter, moving beyond static configurations. MobDHop stands as a key example of mobility-aware multi-hop clustering in MANET research [16].
4. **Performance studies and tradeoffs:** Subsequent research (e.g., Er 2006) examines the tradeoffs associated with increasing d: while a larger d reduces the number of clusterheads and simplifies inter-cluster routing, it can also increase intra-cluster control overhead and make clusters more vulnerable to topological changes. Empirical and simulation-based evaluations—such as those of MobDHop and related algorithms—assess the balance between stability improvements and overhead costs. These studies also compare mobility-aware d-hop schemes with traditional 1-hop clustering approaches, providing critical insights for selecting optimal values of d and clusterhead election strategies based on mobility and traffic patterns [17].
5. **Recent distributed multi-hop methods:** Recent advancements, such as DC2HC (Distributed 2-Hop Clustering), revisit multi-hop intra-clustering to address modern

challenges. These approaches prioritize fully distributed operation, reduced maintenance overhead, and seamless integration with connectivity and routing decisions. They demonstrate the enduring relevance of the d-hop concept, which has been refined to meet contemporary demands—such as scalability, reliability, and energy efficiency—in both MANET and VANET environments [18].

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