

Original Article

Optimization Approaches for Cluster Formation in Mobile Ad-Hoc Networks: A Comprehensive Survey

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ABSTRACT

A new generation of wireless networks, known as mobile ad hoc networks (MANETs), is quickly becoming the backbone of truly autonomous and ever-changing wireless networks. Important issues with these networks, like as energy efficiency, load balancing, routing stability, and scalability, have been successfully addressed using clustering algorithms. This study looks at cluster-based routing and optimization methods in detail to help with choosing the best cluster head and adapting the clustering. Network longevity, energy consumption, and stability are measured for key mobility-aware, energy-efficient, and social-aware algorithms such as LEACH, PEGADyn, GMCA, AREA, and SoCS. Despite their benefits, existing solutions face limitations such as reliance on simulation-based evaluation, assumptions of moderate network sizes or stable links, and trade-offs between energy, latency, and security. The findings highlight the effectiveness of clustering in reducing routing complexity, improving data aggregation, and enhancing overall network performance. However, existing methods are primarily validated through simulations and often rely on assumptions such as stable connectivity or moderate network sizes, which may limit applicability in large-scale and highly dynamic real-world environments.

KEYWORDS

Mobile Ad-Hoc Networks (MANETs), Cluster Formation, Cluster head Selection, Routing Overhead, Scalability, Energy Efficiency.

1. INTRODUCTION

The rapid expansion of wireless communication and the widespread availability of intelligent devices have led to the development of Mobile Ad-Hoc Networks (MANETs) as a key enabler of the Internet of Things (IoT). The MANET's mobile nodes are able to self-organise and communicate with each other using multi-hop wireless links, doing away with the necessity for conventional infrastructure that supports wireless networks [1]. Since no fixed infrastructure is always available or viable in disaster management, military operations, environmental monitoring, or emergency rescue missions, MANETs are a great choice. Despite MANETs' adaptability and flexibility, they confront significant problems with scalability, routing efficiency, and energy consumption [2]. As the network size grows, flat routing schemes become increasingly inefficient due to excessive control overhead, frequent route discoveries, and high computational complexity [3]. The complexity of proactive routing protocols grows quadratically with the number of nodes, whereas reactive approaches experience problems such broadcast storms and delays in route creation. These restrictions reduce MANET performance, especially in large-scale and dynamic environments [4][5].

A number of hierarchical routing systems have been proposed by researchers as potential solutions to these problems; one such strategy is cluster-based routing. Cluster heads (CHs) coordinate the activities of their respective clusters of nodes in this method [6]. Ordinary nodes communicate with their respective cluster head, while gateway nodes connect multiple clusters to facilitate inter-cluster communication. By localizing routing decisions at the cluster level rather than at the individual node level, cluster-based routing significantly reduces control message propagation, enhances route stability, and addresses the scalability problem inherent in flat MANET structures. Optimal cluster head selection and efficient cluster creation are the backbones of MANET cluster-based routing. With so many competing objectives, this selection problem is NP-hard. Key objectives include reducing routing overhead, extending network lifetime, balancing load, and managing node heterogeneity [7]. Traditional deterministic methods struggle with MANETs' dynamic and resource-limited environments. As a result, optimization-based techniques have gained attention. These include heuristic, metaheuristic, and evolutionary algorithms. This paper studies these approaches in depth. It evaluates their scalability, energy efficiency, and adaptability to topology changes. Strengths and limitations are analyzed to guide the design of robust clustering strategies for future MANETs.

1.1. Problem Statement

The growing demand for wireless communication and IoT devices has highlighted the importance of MANETs, which are flexible and infrastructure-less. However, dynamic topology, limited energy, and high routing overhead create challenges in scalability, stability, and efficiency. While cluster-based routing can address these issues, optimal cluster head selection and maintaining stable clusters in dynamic environments remain challenging. Existing methods often focus on single objectives or assume stable conditions, limiting real-world applicability. The necessity for MANET clustering solutions that are resilient, scalable, and energy efficient is what prompted this research.

1.2. Structure of Paper

The paper is organized into various sections. Section II Overview of MANETs covers network architecture, characteristics. Section III explains clustering in MANETs. Section IV present Cluster Formation Algorithms. Section V Optimisation Algorithms discusses. Section VI provides a Literature Review that summarises existing approaches, highlighting objectives, advantages, and limitations. Section VII Conclusion presents key findings and limitations of current techniques.

1.3. An Overview Of Mobile Ad Hoc Networks

The building blocks of a MANET are nodes, which are mobile platforms. Along with formulating them randomly, it can move freely in any direction at any pace. In a network, each node can serve as either a source, a destination, or a router. In a mobile ad hoc network, they function in tandem with other nodes that have lower power, coverage, and data transfer capacities. Due to the recent development, and owing to the popularity of mobile wireless devices, the technological advancements have made it possible for the deployment of such networks for various applications [8]. One such system that is well-suited for tactical operations, disaster recovery, and emergency response is the infrastructure-less mobile ad hoc network, or MANET. Their dynamic topology allows nodes to join or leave freely, forming peer-to-peer multi-hop wireless networks. Data transmission follows a store-and-forward mechanism via intermediate nodes. As mobile hosts (MHs) move, routing paths must be updated to reflect topology changes. For instance, in Figure 1, when MH2 shifts its connection from MH3 to MH4, all nodes must adjust their routing accordingly to maintain communication integrity.

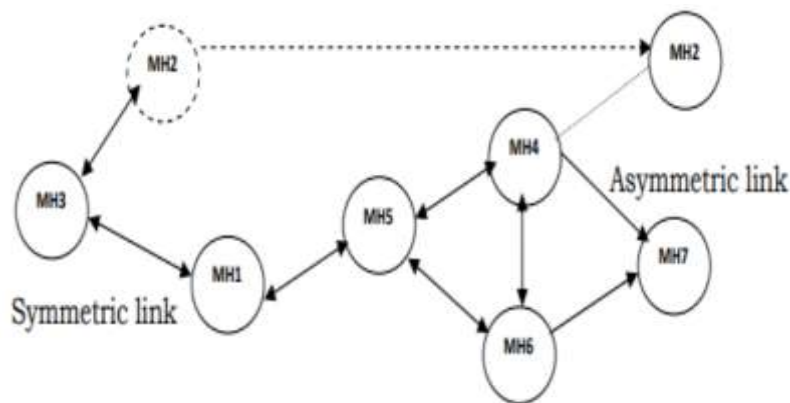


Fig 1 - A Mobile Ad-Hoc Network (Manet)

It is assumed that not all mobile hosts (MHs) are within mutual radio range [9]. Full connectivity would eliminate routing challenges but is impractical due to power constraints, battery limitations, and spatial reuse [10]. The figure also highlights the issue of symmetric vs. asymmetric links. Many protocols assume symmetric communication – e.g., if MH1 can reach MH3, then MH3 can reach MH1 – despite this not always being valid. This simplification is common, as routing in asymmetric networks is significantly more complex.

1.4. Characteristics Of MANETS

In addition to their autonomous and infrastructure-less features, MANETS have other characteristics and complexities.

- The nodes in MANETs are energy-constrained devices, typically battery-powered, with various capabilities.
- The necessary network functionality can only be provided if these devices can dynamically organise themselves.
- Rapid and unpredictable topology changes can occur because devices can freely join or leave the network and migrate at random.
- Traditional issues with MANETs include less scalability, less physical security, time-varying channels, interference, and less reliability.
- These networks are capable of generating new nodes, arranging existing ones, and managing themselves.

2. CLUSTERING IN MOBILE AD HOC NETWORKS

Clustering is a technique that divides sensor nodes into groups, or virtual clusters. Every node in a cluster is responsible for a specific function. Grouping nodes into clusters according to certain criteria and then picking the most efficient node from each cluster to serve as CH is what's known as clustering [11]. See Figure 2 for an illustration of the many benefits of clustering architecture over competing approaches. These include better scalability, less data transmission required due to aggregated and summarised data, fewer relay nodes, load balancing, improved energy consumption, longer network lifetime, and more. These benefits show that clustering is a good way to route WSNs [12].

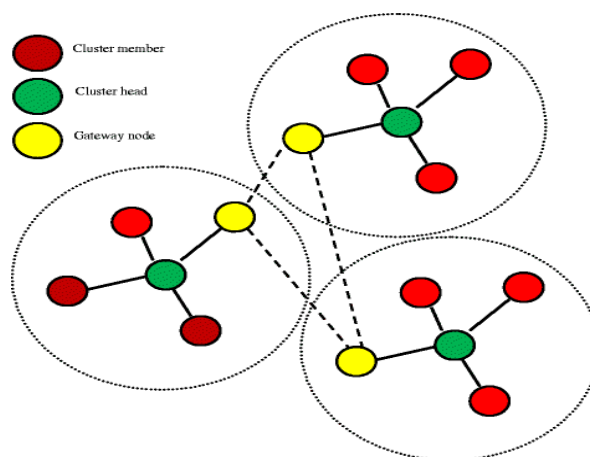


Fig 2 - Clustering In MANET [13]

- **Cluster Head (CH):** A CH's principal role is to coordinate a group of nodes located inside the cluster's physical boundaries [14]. Another important purpose is to gather data from all the nodes in the cluster and transmit it to the next destination.
- **Member Node:** The term "ordinary nodes in a cluster" can describe them as well. A Gateway node is not the same as a Cluster Head. It is devoid of any connections between clusters.

- Gateway Node: It is a non-cluster head node. It is also called a Border node in a Cluster. It is responsible for communication among neighbouring clusters

3. CLUSTER FORMATION TECHNIQUE

The "lowest ID" clustering method selects the Cluster Head from the set of nodes that have the fewest available IDs. Based on the information it learns from hello messages, a node starts the development of a cluster. Except for the node with the lowest ID, if it is a member node of the cluster that has already been designated as the Cluster Head, it includes all of its neighbours that are linked in both directions. In order to highlight the new Cluster Head's function inside the cluster, the first field in its addressing messages afterwards will be changed from "undecided" to "cluster head."

3.1. Direct Trust Evaluation Technique

The method relies on determining the trustworthiness of each node in the cluster before choosing a leader [15]. Data type, packet transmission rate, delivery rate, dropped packets, and other metrics are utilised to arrive at this trust rating; the cluster head is then selected by comparing this trust rating to a threshold value.

3.2. Cluster-Based Route Discovery Algorithm(Aodv)

The focus of this technique is on two specific situations in clustered networks [16]. Initially, a route is discovered within the same cluster, where the sender and receiver nodes are physically located. Second, when the nodes that give and receive the data are in different clusters, the algorithm uses the concept of a history table to remember specifics about such transfers. In the long run, this helps and saves energy and time.

3.3. Connectivity-Based Clustering

The leader of the cluster is elected based on the connection. Every node in a cluster is regarded a member of the cluster, with the node with the most neighbours serving as the cluster head.

3.4. Energy Efficient Clustering (Fwcabp)

The abbreviation "FWCABP" refers to a battery-powered, flexible weighted clustering algorithm. Power consumption of individual nodes is the basis of this clustering process. The elimination of nodes with low energy power consumption is being done in order to prevent them from becoming the cluster head. During the cluster creation phase, each node updates its neighbours on its state and compiles a list of its neighbours through the use of messages [17].

3.5. Clustering Schemes In Mobile Ad Hoc Networks

A node's mobility level dictates the CH to be used in a mobility-based clustering scenario. The reason being, MANET nodes can roam, hence it's crucial to monitor each cluster node's mobility level. Therefore, the degree of mobility of a node is a critical consideration for choosing a CH since it is a significant constraint that can affect the stable and efficient operation of the network. Movement pattern

is sluggish in comparison to other nodes, but it has abundant energy resources and stable connectivity with other nodes in the group.

Table 1: Analysis of Mobility-Based Clustering Algorithm

Algorithm	CH selection	Advantages	Drawback
MobDHop [19]	The relative movement of nodes (changes in the distance between them over time).	Reduce the number of clusters to maximise relative mobility while also improving stability within the context of the group's mobility pattern.	Due to high dynamics, more overhead occurs in relative mobility.
CMCA [20]	The least mobile node is selected as the CH.	Achieve scalability, robustness in large-scale networks.	More hop count inside the cluster can affect CH efficiency.
SCHM [21]	Average relative speed of a node.	Provides more stable clustering in high mobility, along with the solution to handle connection breakups.	It requires more energy to exchange control messages.
MPBC [22]	Lowest relative mobility.	Predicting how people move about allows us to cut out some superfluous cluster merges.	The shorter average lifetime of CH.
GMCA [23]	Relative lower mobility with great energy reserve and higher connectivity.	Enhance network stability, scalability and provide better performance during CH change.	A change in CH affects during mobility at high speed.

The analysis of algorithms based on mobility is presented in Table I. Each scheme's CH selection criteria and advantages and disadvantages are displayed. Figure 3 shows the results of comparing these systems' performance.

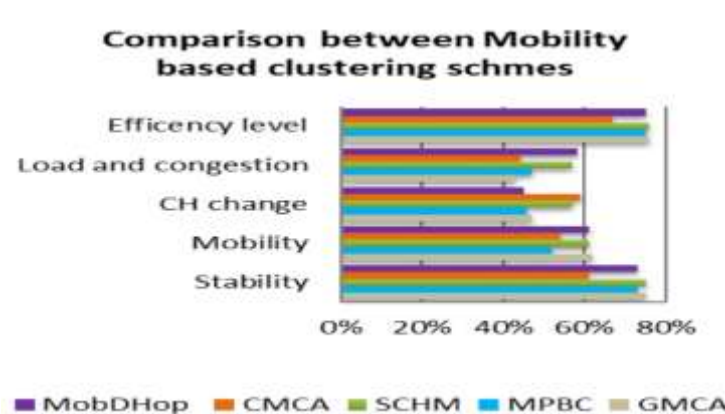


Fig 3 - Performance Comparison between Mobility Schemes

CMCA is about as safe as MobDHop SCHM, MPBC, and GMCA. On the other hand, GMCA and SCHM are more stable when you look at the problems with each scheme. See how these systems stack up against one another in Fig. 6. The stability level of CMCA is average when compared to MobDHop,

SCHM, MPBC, and GMCA; however, SCHM and MobDHop are more stable than GMCA and MPBC, respectively. All of these schemes have a modest CH change overall, but CMCA and SCHM have a somewhat significant CH change compared to the others, which could lead to cluster overlapping. Low mobility is an area where all of these strategies excel. In GMCA and SCHM, the load and congestion are balanced. When contrasted with DWCA and FWCA, EWCA, EMSWCA, and NWBCA all exhibit very high levels of efficiency.

4. OPTIMIZATION ALGORITHM IN CLUSTERING

Improving the effectiveness and efficiency of WSNs is largely accomplished through optimisation approaches. Computational Intelligence (CI) and Machine Learning (ML) algorithms, when combined with nature-inspired optimization techniques [24], enhance network performance in WSN. In large-scale deployments, the network lifetime is improved by the widely used LEACH [25], which picks cluster heads (CHs) based on computation and Received Signal Strength (RSS). However, its single-hop configuration limits scalability. Intelligent clustering aims to extend network lifetime in multi-hop environments. ML/CI-based clustering algorithms are typically categorized into Fuzzy Logic, Neural Networks, and Geneptic Algorithms. As shown in Figure 4, key paradigms include FL, RL, NN, and SI.

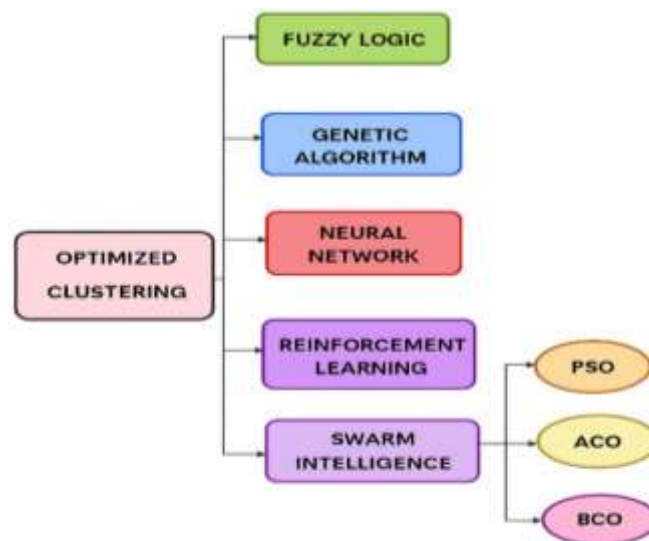


Fig 4 - Classification Of Optimized Clustering Algorithms

There are various techniques of clustering.

- Fuzzy Logic: Mostly fuzzy logic is utilized to solve the difficulties of uncertainty in the system without the need for full data about the system. FL is a method of variable processing that permits multiple values to be handled through the same variable.
- Genetic Algorithms (GAs): GAs are evolutionary algorithms inspired by natural selection processes. They are used in WSNs to solve challenging optimization problems, such as sensor node placement and network clustering. GAs use genetic operators such as mutation, selection, and crossover to iteratively evolve populations of candidate solutions, searching the solution space and converging on optimal or near-optimal configurations [26].

- Neural Network (NN): The NN methods are a process of mathematical models that are inspired by biological neurons. Each neuron is connected to multiple neurons. A NN comprises the neurons that are arranged in input, output, and hidden layers, where the NN acquires various locations and establishes connections between the layers.
- Swarm Intelligence: The Swarm Intelligence (SI) is an algorithm that attempts to design techniques or devices for distributed problem-solving, which is inspired by the social insects' collective behaviour and various biological societies. Many SI methods depend on the characters of bird flocks, insect and fish schools etc. These techniques applied for CH selection in WSN
- Wireless sensor networks can be fine-tuned for maximum performance and efficiency by careful consideration of the situation at hand and the outcomes sought by network designers.

5. LITERATURE REVIEW

The clustering algorithm literature review contains numerous articles about mobile ad hoc networks. The following protocols are associated with this paper.

Hossen, Hossen and Islam (2020) suggest a technique for clustering in VANET that makes use of parked cars as nodes in a hierarchy, dubbed the PCCH scheme. Vehicles in the PCCH model group together under the leadership of selected cluster heads (CHs), who in turn relay information to parked vehicles. Compared to models based on parked cars without clustering, PCCH achieves an energy efficiency that is around 60% greater, according to numerical simulations [27].

Sherazi, Iqbal and Grieco (2019) suggest an Adaptive Resilience Algorithm (AREA) to reformat clusters in VANETs, which accounts for several interconnected parameters such as travel direction, relative velocity, and inter-nodal distance, resulting in more stable and long-lasting clustering. The simulation results clearly show that the proposed method is robust and stable [28].

Abbas, Audah and Alduais (2018) suggested a new approach known as intelligent cluster head (ICH) to improve cluster stability while simultaneously decreasing the amount of base station (BS) uplink connections. The method uses an existing mobile BS when possible, reducing uplink connections and CHs by 53.92%, thereby improving system stability, validated via MATLAB simulations with real data [29].

Raghavan et al. (2018) propose PEGADyn, a dynamic state algorithm-based, cutting-edge, energy-efficient routing protocol for ad hoc networks. In order to reduce communication overhead and increase the lifetime of the network, PEGADyn uses energy-level selection for CHs and dCHs to form virtual grids and clusters. The simulation results show that compared to Dynamic State and PEGASIS, it has better efficiency and throughput [30].

Jang, Park and Shah (2017) showcased a novel approach that utilizes a mobile ad hoc cloud, which is a group of interconnected mobile devices, to operate an automated video surveillance program. The cloud is like a virtual supercomputer node. They suggested a work allocation approach to meet the real-

time needs of automated video surveillance applications. Energy efficiency and activities with tight deadlines are the main concerns of the proposed design as contrasted with current methods [31].

Muralidhar and Madhavi (2017) primarily address the operational constraints of MANETs, which present a number of obstacles to practical implementation in the business sector. The paper begins by outlining the history of mobile ad hoc networks (MANETs), then moves on to discuss their practical uses, and finally touches on their operational constraints. In order to successfully bring MANETs to the commercial realm, the operational restrictions of these networks must be eliminated [32].

Conceição and Curado (2016) offer a Social-aware Clustering Scheme (SoCS) that takes into account the past relationships between nodes in order to revamp clustering management processes. Each node keeps track of its previous connections to nearby nodes in the hopes of bettering the efficiency of future cluster formations. An analysis of SoCs was conducted using the SNT mobility model, which evaluates traffic performance, clustering, and routing. The results demonstrate a significant improvement in overall performance, proving that social awareness is a quality attribute in clustering strategies [33].

Although numerous clustering and routing approaches have been proposed for VANETs and MANETs, most existing solutions are limited in their applicability to large-scale, dynamic, and heterogeneous environments. Many methods improve energy efficiency, intrusion detection, or cluster stability but rely on assumptions like parked cars or stable connectivity. Most are simulation-based and overlook scalability, adaptability, and interoperability in real-world vehicular networks. Therefore, the major research gap lies in the absence of a holistic clustering framework that can simultaneously ensure energy efficiency, security, stability, and real-time responsiveness. Table II presents a virtual overview of previous research, describing their aims, methods, benefits, drawbacks, and areas of weakness.

Table 2: Summary of Existing Clustering and Routing Approaches in Mobile Ad-Hoc Networks

Author	Objective	Approach	Advantages	Challenges	Research Gap
Hossen, Hossen & Islam, 2020	Improve energy efficiency in VANETs using parked cars	Clustering Hierarchy Based on Parked Cars (PCCH): In the absence of RSUs, CHs act as relays using parked cars.	~60% higher energy efficiency than non-clustered models	Dependence on availability and density of parked cars	Lack of evaluation in highly dynamic urban scenarios and large-scale real-world deployments
Sherazi, Iqbal & Grieco, 2019	Achieve stable clustering despite node mobility	Adaptive Resilience Algorithm (AREA) using direction, velocity & inter-nodal distance	Robust and stable clustering with longer lifetime	Requires frequent metric updates, adding overhead	Real-world vehicular mobility patterns not fully explored

Abbas, Audah & Alduais, 2018	Enhance cluster stability and reduce BS connections	Intelligent Cluster Head (ICH) selection with mobile BS support	Reduced CH count by 53.92%, improved stability	Assumes availability of mobile BS, may not scale	Needs validation in heterogeneous VANETs and hybrid networks
Raghavan et al., 2018	Extend network lifetime with energy-efficient routing	PEGADyn: Hybrid of PEGASIS & Dynamic State with CH/dCH selection	Reduced communication overhead, increased throughput, longer lifetime	More complex CH/dCH selection logic	Limited to simulation; lacks real vehicular network validation
Jang, Park & Shah, 2017	Enable real-time video surveillance over MANET	Mobile Ad Hoc Cloud with deadline-aware task allocation	Meets real-time and energy efficiency requirements	Heavy reliance on stable MANET connectivity	Needs scalability tests for large-scale, latency-sensitive IoT applications
Muralidhar & Madhavi, 2017	Analyze operational challenges of MANETs	Analytical study of bandwidth, energy, mobility & storage constraints	Identifies key limitations for commercialization	Does not propose a concrete solution	Research required on overcoming constraints for large-scale MANET adoption
Conceição & Curado, 2016	Improve clustering with social-awareness	Social-aware Clustering Scheme (SoCS) using link history & SNT model	Better clustering, routing & traffic performance	Relies on accurate link history, may fail in sparse networks	Requires integration with real vehicular mobility and heterogeneous environments

6. CONCLUSION AND FUTURE WORK

MANETs are multi-hop wireless networks with dynamic, low-power, bandwidth-constrained nodes. It is possible to improve stability and scalability by clustering the mobile nodes in response to this demanding environment. Clustering is a method of arranging mobile nodes into groups and electing one node to act as the network manager. In this study, examine how different clustering methods centre on distinct measures of performance. Measures of performance. This study analyzed clustering and optimization techniques for MANETs, highlighting improvements in cluster head selection, scalability, energy efficiency, and routing stability. Protocols such as LEACH, PEGADyn, GMCA, AREA, and SoCS demonstrate enhanced network lifetime, reduced control overhead, and better overall performance. However, most existing methods are simulation-based and rely on assumptions such as stable connectivity or moderate network size, limiting their applicability in large-scale and highly dynamic real-world scenarios. However, several challenges remain, including high node mobility, frequent topology changes, limited energy resources, and reliance on simulation-based evaluations. Future research should focus on real-world deployment, adaptive hybrid algorithms, scalable and secure clustering protocols,

and multi-objective optimization frameworks that balance energy, latency, throughput, and reliability to design robust, efficient, and practical MANET and VANET architectures.

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