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Review Article

Uneven Clustering in Wireless Sensor Networks: A Systematic Review

Chan Kai Ming, Wang Ho
Department of Computer Science, The Hang Seng University of Hong Kong, Hongkong
Corresponding author: chankoimin9@gmail.com

Abstract

Wireless Sensor Networks (WSNs) consist of numerous sensor nodes powered by batteries with limited energy, making efficient energy management a fundamental challenge for ensuring reliable network operation and extending network lifetime. To address this challenge, researchers have proposed various optimization techniques, among which clustering has emerged as one of the most effective approaches for improving energy efficiency and reducing communication overhead. Cluster-based WSNs offer several advantages over traditional network architectures, including enhanced bandwidth utilization, balanced energy consumption, improved network scalability, reduced routing complexity, increased link reliability, lower transmission delay, and greater network stability. Clustering techniques are generally classified into even clustering and uneven clustering. However, even clustering often suffers from the hotspot problem, where cluster heads located near the base station consume energy more rapidly due to increased data forwarding responsibilities, leading to premature node failure and reduced network lifetime. Uneven clustering addresses this issue by creating clusters of varying sizes, enabling more balanced energy consumption among cluster heads and minimizing communication load. This approach effectively mitigates the hotspot problem, improves load balancing, enhances network reliability, and prolongs the operational lifetime of WSNs. This paper presents a comprehensive review of uneven clustering techniques, discussing their design principles, classification, key characteristics, and recent advancements. Furthermore, various uneven clustering algorithms are systematically analyzed and compared based on their energy efficiency, load balancing capability, communication performance, and overall effectiveness in extending the lifespan of wireless sensor networks.

Keywords

Wireless Sensor Networks (WSNs); Uneven Clustering; Cluster Head; Energy Efficiency; Load Balancing; Hotspot Problem; Network Lifetime; Routing Protocols; Energy Optimization; Sensor Networks

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1. Introduction

Wireless Sensor Networks (WSNs) have become one of the most important technologies in modern wireless communication due to their wide range of applications in different fields [1,2]. Because of their growing importance, WSNs continue to be an active area of research. One of the major challenges in designing a WSN is efficient energy management, as sensor nodes operate on batteries with limited power. These sensor nodes also have limited memory, processing capability, and communication resources. However, recent advancements in CMOS and nanotechnology have enabled the development of smaller, low-cost, and more efficient sensor nodes. A sensor node consists of a microprocessor, battery, transceiver, and sensing unit. These nodes are capable of organizing themselves into a network without requiring any fixed infrastructure. A typical WSN contains hundreds or even thousands of sensor nodes that can sense environmental parameters such as temperature, humidity, pressure, vehicle movement, acoustic signals, and infrared radiation [3]. The sensed data are processed by the onboard processor and transmitted to the base station (BS) either through single-hop or multi-hop communication.

WSNs support two types of communication: intra-cluster communication, where data are exchanged between cluster members and their Cluster Head (CH), and inter-cluster communication, where data are transmitted between different clusters or from CHs to the BS. Small clusters generally use single-hop communication, whereas larger clusters rely on multi-hop communication to improve energy efficiency. Sensor nodes send their data only to their respective CHs, which aggregate the received information before forwarding it to the BS, thereby reducing redundant transmissions and saving energy. To avoid communication collisions within a cluster, each CH assigns a Time Division Multiple Access (TDMA) schedule to its member nodes. Similarly, Code Division Multiple Access (CDMA) codes are used to minimize interference among neighboring clusters [3].

Due to these advantages, WSNs are widely used in applications such as military surveillance, agriculture, environmental monitoring, disaster management, healthcare, industrial automation, and inventory management [4]. They are particularly useful in remote or hazardous environments where human access is difficult, including forests, battlefields, deep-sea regions, no-man's-land, and complex industrial or research facilities [5].

In WSNs, wireless communication consumes significantly more energy than sensing or data processing [6]. Therefore, developing energy-efficient communication techniques is essential for extending the operational lifetime of the network. Clustering is one of the most effective approaches for achieving this objective. In a clustering-based WSN, sensor nodes are grouped into clusters, which may be homogeneous (consisting of similar sensor nodes) or heterogeneous (consisting of different types of sensor nodes) [5].

Based on cluster architecture, clustering techniques are broadly classified into even clustering and uneven clustering, as illustrated in Fig. 2. Even clustering often suffers from the hotspot problem because cluster heads located near the BS handle more forwarding traffic and consume energy more quickly. Uneven clustering addresses this issue by creating smaller clusters near the BS and larger clusters farther away, thereby balancing the communication load among cluster heads and improving network lifetime [7]. In recent years, numerous even and uneven clustering techniques have been proposed to improve the energy efficiency of WSNs [8,9]. However, comprehensive and up-to-date surveys of uneven clustering protocols remain limited. Therefore, this paper presents a detailed review of uneven clustering techniques, discussing their objectives, advantages, limitations, taxonomy, cluster head selection methods, clustering approaches, and key characteristics. The paper also provides a systematic analysis of existing uneven clustering algorithms and their role in improving energy efficiency and extending the lifetime of wireless sensor networks.

2. Literature Review

The main objective of uneven clustering is to solve the hotspot problem, which occurs when some cluster heads consume more energy than others, resulting in a shorter network lifetime. Similar to traditional clustering, uneven clustering also aims to achieve load balancing, increase network lifetime, improve data aggregation, provide fault tolerance, support scalability, and maintain a stable network topology. Based on their working principles, uneven clustering algorithms are broadly classified into three categories: Probabilistic, Deterministic, and Preset (Heuristic)-based clustering algorithms [10].

2.1. Probabilistic Algorithms

In probabilistic clustering algorithms, cluster heads (CHs) are selected randomly without following any predefined rules. These algorithms are simple, energy-efficient, and require low communication overhead. Their main goal is to extend the lifetime of WSNs while keeping the time and message complexity low. Probabilistic algorithms are further divided into Random Probabilistic Algorithms and Hybrid Probabilistic Algorithms [11].

2.1.1. Random Probabilistic Algorithms

Random probabilistic algorithms select cluster heads randomly, making them simple to implement with low computational and communication overhead. Several well-known algorithms are discussed below.

2.1.1.1. LEACH-DCH

LEACH with Deterministic Cluster Head (LEACH-DCH) is an improved version of the LEACH protocol that focuses on reducing energy consumption in wireless sensor networks. It enhances the cluster head selection process by using deterministic criteria based on local network information instead of random selection. Each sensor node independently decides whether it should become a cluster head without communicating with the base station or other nodes. The protocol also introduces three network lifetime parameters: First Node Dead (FND), Half Nodes Alive (HNA), and Last Node Dead (LND). Simulation results show that LEACH-DCH improves energy efficiency and increases the network lifetime by nearly 30% compared with the original LEACH protocol [12].

2.1.1.2. TL-LEACH

Two-Level LEACH (TL-LEACH) extends the original LEACH protocol by introducing two levels of cluster heads: primary and secondary cluster heads. Unlike the single-level hierarchy in LEACH, this two-level structure reduces the communication distance between sensor nodes and the base station, resulting in lower energy consumption. TL-LEACH is especially suitable for large and dense wireless sensor networks because it provides better scalability, robustness, and energy efficiency. It also delivers more data packets successfully and extends the network lifetime by approximately 30% compared with the original LEACH protocol [13].

2.1.1.3. LEACH-C

LEACH-C (Centralized LEACH) is a centralized clustering protocol in which the base station is responsible for selecting cluster heads. The selection is based on the residual energy of sensor nodes, giving preference to nodes with higher remaining energy. After selecting the cluster heads, the base station organizes clusters by minimizing the total communication distance between cluster heads and their member nodes. This optimized cluster formation reduces overall energy consumption and improves network performance.

Compared with the original LEACH protocol, LEACH-C extends the network lifetime by about 5–10% while significantly reducing energy consumption [14].

2.1.1.4. EEMRP

Energy-Efficient Multi-hop Routing Protocol (EEMRP) was developed to overcome the limitations of traditional homogeneous and heterogeneous clustering protocols, where cluster heads (CHs) experience heavy communication loads, leading to rapid energy depletion and reduced network lifetime. In many existing approaches, the location of sensor nodes is not properly considered during cluster formation, resulting in inefficient energy utilization. To address these issues, EEMRP divides the wireless sensor network into unequal grids, where larger grids are created farther from the base station (BS) and smaller grids are placed closer to it. This arrangement provides better load balancing and more efficient energy utilization. The protocol uses single-hop communication for nodes located near the BS and multi-hop communication for distant nodes. EEMRP also introduces Communication Manager (CM) nodes to assist cluster heads in data transmission and cluster management, thereby reducing the communication burden on CHs. The cluster head selection process considers multiple factors, including the residual energy of nodes, their locations, and the network area ranking. As a result, the protocol improves cluster head placement, reduces communication costs, and prevents premature node failures. Simulation results show that EEMRP achieves better energy efficiency, higher transmission capacity, and extends the network lifetime and scalability by 17.5–25.2% compared to Multi-hop EEBCDA [14].

2.1.1.5. PRODUCE

Probability-Driven Unequal Clustering (PRODUCE) is a distributed and randomized clustering protocol designed to solve the hotspot problem in wireless sensor networks. It creates unequal-sized clusters using localized probability values, allowing the network to distribute communication load more effectively. The protocol is particularly suitable for dense sensor networks, where extending network lifetime is a primary objective. In PRODUCE, cluster heads located close to the base station mainly handle inter-cluster communication, while cluster heads farther from the base station focus on intra-cluster communication. This balanced workload reduces excessive energy consumption near the base station and minimizes the hotspot problem. The protocol also employs stochastic geometry for inter-cluster routing, which further improves communication efficiency. By balancing energy consumption among cluster heads, PRODUCE significantly increases network coverage time and extends the operational lifetime of the wireless sensor network. Simulation results demonstrate that PRODUCE effectively balances energy usage and enhances the overall lifetime of WSNs [15].

2.1.1.6. FLCMN

Fuzzy Logic for Multi-hop Networks (FLCMN) divides network operation into equal rounds, and each round consists of two phases: the clustering phase and the data transmission phase. The protocol uses a Fuzzy Inference System (FIS) to select cluster heads (CHs). The CH selection is based on three input parameters: Remaining Energy of the Node (REN), Average Remaining Energy of Neighbor Nodes (RENN), and the rank of the node. During cluster formation, each node calculates its suitability and broadcasts its status. If a sensor node receives requests from multiple cluster heads, it joins the nearest one. FLCMN supports multi-hop communication between cluster heads and employs a Fibonacci sequence-based routing strategy to reduce unnecessary data transmissions. This approach effectively addresses the hotspot problem, balances the distribution of sensor nodes among clusters, and improves energy utilization. Simulation results show that FLCMN achieves better energy balancing and a longer network lifetime than existing protocols such as EAMMH, DFLC, and LEACH [16].

2.1.1.7. EEGBR

Energy-Efficient Grid-Based Routing (EEGBR) is designed to reduce energy consumption and increase the lifetime of wireless sensor networks. The network is divided into grids, and each grid selects a Grid Coordinator (GC) using fuzzy logic. The selection is based on factors such as residual energy, distance from the sink, and node degree. The Grid Coordinator acts as a relay node and determines the most energy-efficient routing path by minimizing the number of communication hops. Fuzzy rules are also used for node deployment, energy analysis, cluster formation, cluster head selection, and routing decisions. By reducing communication overhead and improving routing efficiency, EEGBR minimizes energy consumption and extends network lifetime. Simulation results demonstrate that EEGBR provides lower energy consumption, reduced communication delay, and improved network lifetime. The protocol can also be extended to support mobile sensor networks in future applications [17].

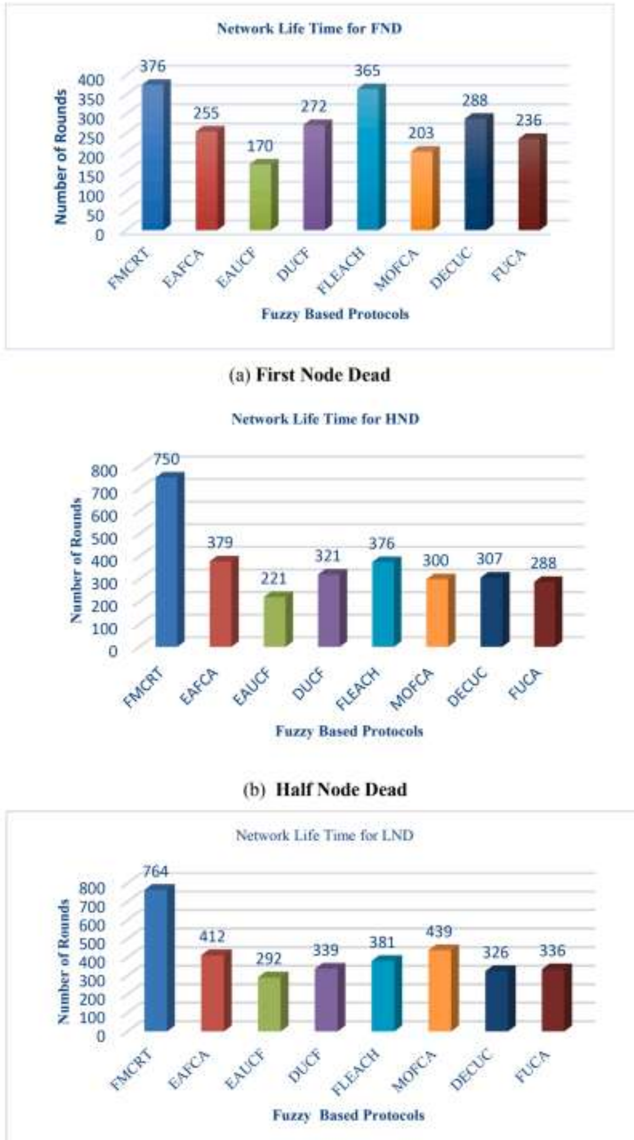
2.1.1.8. FUCA

Fuzzy-Based Unequal Clustering Algorithm (FUCA) is proposed to solve the energy hole (hotspot) problem, where sensor nodes located near the sink deplete their energy more quickly than other nodes, causing network partitioning and reducing network lifetime. FUCA creates unequal-sized clusters to balance energy consumption across the network. Cluster heads are selected using a fuzzy logic approach based on three parameters: residual energy, distance to the base station, and node density. The Mamdani Fuzzy Inference System is used to calculate the node rank and competition radius for cluster head selection. Unlike LEACH, which randomly selects cluster heads, FUCA chooses cluster heads according to their suitability, resulting in more balanced energy consumption. FUCA also performs better than EAUCF and overcomes the cluster head selection limitations of MOFCA. Simulation results indicate that FUCA achieves better energy balancing, longer network lifetime, and stable performance regardless of sink location or node density [18].

2.1.1.9. FLEACH

Fuzzy Logic-based Energy-Efficient Cluster Head (FLEACH) is an unequal clustering protocol that uses fuzzy logic to select cluster heads efficiently. The protocol operates in three stages: cluster head selection, cluster formation, and data transmission. Cluster heads are selected based on three important parameters: residual energy, distance from the base station, and node degree. A Fuzzy Inference System (FIS) evaluates these parameters, while the Centre of Area (COA) method is used to convert the fuzzy output into a crisp value for selecting the cluster head. After the cluster heads are selected, they broadcast advertisement messages, and nearby sensor nodes join the most suitable cluster. Data transmission then takes place through the selected cluster heads. Simulation results show that FLEACH significantly reduces energy consumption compared with the original LEACH protocol. For networks with 100 nodes, FLEACH reduces energy consumption by

12.09%, while for 200-node networks, the reduction reaches 36.20%. Consequently, FLEACH considerably improves network lifetime and overall energy efficiency compared with LEACH [19].



(a) First Node Dead

(b) Half Node Dead

(c) Last Node Dead,

Fig.1. Fuzzy based protocol comparison [20]

3. Discussion and Comparison

Comparative results of the fuzzy-based clustering protocol are shown below in Fig. 1 with the help of the bar chart area [56]. Algorithms require the network`s global information and are fully managed by the base station which makes it impractical for various applications. That results in a tradeoff between QOS and the simplicity of the algorithm. Application application-specific situations, this is the better choice as compared to the other. Clustering algorithms of weight-based type are iterative which causes the message complexity. Compound-based unequal clustering uses various types of metrics such as the Sierpinski triangle, linked graphs, etc., to formulate energy-efficient clustering. Although we tried to review all methods, a few clustering techniques have not been examined yet. Maximum clustering methods are static, and cannot adopt changes if the network varies, then dynamic methods of clustering can be adopted. In a clustered type of wireless sensor network, three parts cluster's members, CHs, and lastly the BS. Wireless sensor networks with movement lead to regular changes in topology and overheads are increased. WSNs are mostly data-centric and require datacentric methods. Algos are invented mostly for the proactive type and few numbers of algorithms are available for the reactive types of networks. In the future reactive-type clustering methods may be investigated more. Several uneven types of clustering are described in this paper. Some of the fuzzy types of algorithms are also shown in Fig. 1 and from the results we can say that as compared to other fuzzy logic technologies FMCRT is more energy efficient and gives the longest life span.

Table 1: Comparison of Probabilistic Type Uneven Clustering Protocols [21]

Protocol	Cluster Count	Intra-Cluster	Inter-Cluster	Node Type	CH Selection	Nature
LEACH-DCH	Variable	Single-hop	Multi-hop	Homogeneous	Random	Proactive
TL-LEACH	Variable	Single-hop	Multi-hop	Homogeneous	Random	Proactive
LEACH-C	Variable	Single-hop	Multi-hop	Homogeneous	Random / BS	Proactive
EEMRP	Variable	Single-hop	Multi-hop	Homogeneous	Random	Proactive
PRODUCE	Variable	Single-hop	Multi-hop	Homogeneous	Random	Proactive
EDUC	Variable	Single-hop	Multi-hop	Homogeneous	Random	Proactive
LUCA	Variable	Single-hop	Multi-hop	Homogeneous	Random / Dist	Proactive
K-means-LDC	Variable	Single-hop	Multi-hop	Homogeneous	Hybrid	Proactive
MH-LEACH	Variable	Multi-hop	Multi-hop	Homogeneous	Hybrid	Proactive
Q-LEACH	Variable	Single-hop	Multi-hop	Homogeneous	Hybrid	Proactive
HEED	Variable	Multi-hop	Multi-hop	Homogeneous	Hybrid	Proactive
EEUC	Variable	Single-hop	Multi-hop	Homogeneous	Hybrid	Proactive
UCR	Variable	Single-hop	Multi-hop	Homogeneous	Hybrid	Proactive
COCA	Variable	Single-hop	Multi-hop	Homogeneous	Hybrid	Proactive

Table 2: Comparison of Deterministic Type Uneven Clustering Protocols [21]

Protocol	Method Category	Intra-Cluster	Inter-Cluster	CH Selection Basis	Nature
UDCH	Weight-based	Single-hop	Multi-hop	Weight / Multi-obj	Proactive
Node Ranked-LEACH	Weight-based	Single-hop	Multi-hop	Node Rank / Weight	Proactive
EADUC	Weight-based	Single-hop	Multi-hop	Residual Energy / Dist	Proactive
FMCR-CT	Fuzzy-based	Single-hop	Multi-hop	Fuzzy Rules (Energy, Dist)	Proactive
FL-EEC/D	Fuzzy-based	Single-hop	Multi-hop	Fuzzy FIS (Mamdani)	Proactive
FUCA	Fuzzy-based	Single-hop	Single-hop	Fuzzy Logic / Distance	Proactive
FLECH	Fuzzy-based	Single-hop	Single-hop	Fuzzy Logic	Proactive
EBUC	Heuristic	Single-hop	Multi-hop	PSO Optimization	Proactive
GAEEP	Heuristic	Single-hop	Multi-hop	Genetic Algorithm	Proactive
IPSO	Heuristic	Single-hop	Multi-hop	Improved PSO	Proactive
PEG-ant	Compound	Single-hop	Multi-hop	ACO + Chain	Proactive
EDDUCA	Compound	Single-hop	Multi-hop	Sierpinski Triangle	Proactive

Table 3: Comparison of Preset Type Uneven Clustering Protocols [21]

Protocol	Cluster Count	Intra-Cluster	Inter-Cluster	CH Placement	Nature
UCS [91]	Variable	Single-hop	Multi-hop	Preset Concentric Circles	Proactive

4. Conclusion

This paper presented a comprehensive review of uneven clustering techniques for Wireless Sensor Networks (WSNs) with a focus on improving energy efficiency and extending network lifetime. The study discussed the challenges of limited battery power in sensor nodes and highlighted clustering as an effective solution for reducing energy consumption. Various uneven clustering protocols were reviewed and classified into three 20major categories: probabilistic, deterministic, and heuristic-based approaches. Their objectives, characteristics, advantages, and limitations were compared to provide a clear understanding of their applicability. Probabilistic methods are suitable for simple and fast clustering, deterministic approaches provide better reliability and stability, while heuristic-based techniques are more effective for complex and application-specific scenarios. The study also compared these protocols based on cluster properties, cluster head (CH) selection, and clustering mechanisms.

The review shows that uneven clustering performs better than even clustering by effectively addressing the hotspot problem and balancing the communication load among cluster heads. Several strategies, including distance-based cluster sizing, residual energy-based CH rotation, multi-hop communication, load balancing, energy-aware CH selection, relay nodes, data aggregation, hierarchical clustering, and sleep/wake scheduling, contribute to improving network performance and lifetime. Furthermore, the paper identified important performance metrics for evaluating uneven clustering techniques, such as energy consumption, residual energy, energy balancing, and network lifetime measured through First Node Dead (FND), Half of the Nodes Dead (HND), and Last Node Dead (LND). Overall, uneven clustering remains a promising approach for developing energy-efficient, reliable, and scalable wireless sensor networks for future applications.

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Conflict of Interest

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All authors participated equally for researching and writing the contents of this paper.

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