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Enhanced Self-Organization Clustering with Novel Techniques in Mobile Wireless Sensor Networks

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Abstract: Self-organization clustering protocols in mobile wireless sensor networks (MWSNs) are designed to enhance energy efficiency and prolong the lifespan of sensor nodes. However, these protocols face significant challenges when applied to large-scale sensor fields. A primary issue arises when cluster-head nodes broadcast Advertisement Messages over vast areas, leading to energy inefficiencies and the emergence of non-receiving nodes, particularly when transmission ranges are constrained to conserve power. This study investigates the relationship between the transmission range and the prevalence of non-receiving nodes, presenting a novel solution to address these limitations. The proposed Two-Tier Clustering (TTC) method introduces a two-step clustering process. Initially, cluster-head nodes are distributed across the network field using a probabilistic selection mechanism. In the second phase, nodes that failed to receive Advertisement Messages during the first step are addressed, further enhancing cluster formation and eliminating clumping of cluster-head nodes. This adaptive approach ensures a more even distribution of clusters and reduces the number of nodes excluded from the network. Simulation results validate the effectiveness of TTC, showing reductions in non-receiving nodes by over 12% compared to LEACH-Mobile and 27% compared to MBC. Additionally, when transmission radii are optimized, TTC achieves an 84% reduction in non-receiving nodes compared to traditional approaches. This improvement reduces data loss, enhanced energy efficiency, and robust network operation in dynamic and large-scale environments. The findings highlight TTC as a significant advancement in optimizing clustering protocols for MWSNs, ensuring more reliable and sustainable sensor network performance.

Keywords: Self-organization clustering, Two-tier clustering, Energy efficiency, Mobile wireless sensor networks, Non-receiving nodes

1. Introduction

Mobile Wireless Sensor Networks (MWSNs) are integral to modern technology, enabling various applications, from smart cities and environmental monitoring to healthcare systems and military operations. These networks consist of spatially distributed, energy-constrained sensor nodes that collaboratively collect, process and transmit data to central base stations.

Unlike static Wireless Sensor Networks (WSNs), MWSNs face unique challenges due to the mobility of nodes, which introduces dynamic topology changes and complicates communication processes. Cluster-based routing protocols have emerged as a vital solution to address these challenges. These protocols optimize energy usage by organizing sensor nodes into clusters and assigning specific nodes as cluster heads to aggregate and relay data, thus extending the network's operational lifetime.

Despite their advantages, conventional cluster-based protocols, such as the widely studied Low Energy Adaptive Clustering Hierarchy (LEACH), often fall short when applied to MWSNs with large and dynamic sensor fields. LEACH and its derivatives assume uniform node distribution and static field size, typically 50m x 50m, conditions rarely met in real-world scenarios. When sensor fields expand, cluster heads must broadcast Advertisement Messages over larger areas, consuming significant energy and leading to non-receiving nodes—sensor nodes that fail to connect to any cluster. Non-receiving nodes result in data loss and degrade the network's robustness and efficiency. These challenges highlight the critical need for adaptive clustering methods tailored to mobile and large-scale sensor fields.

Recent research has explored enhancements to traditional clustering protocols. Deng et al. [1] introduced mobility-aware clustering approaches, but their methods struggled to balance energy efficiency with dynamic node mobility. Xu et al. [2] and Lehsaini et al. [3] proposed multi-sink and energy-efficient clustering algorithms, respectively, yet these failed to address the exclusion of nodes in mobile contexts. Kim [4] emphasized data aggregation in mobile environments, while Kumar et al. [5] leveraged mobility metrics to improve clustering decisions. However, these efforts collectively fail to address the persistent issue of non-receiving nodes, leaving a significant gap in developing scalable and robust solutions for MWSNs.

This study proposes a novel Two-Tier Clustering (TTC) method to bridge this gap. Unlike traditional clustering protocols, TTC employs a two-phase clustering approach to ensure an even distribution of cluster-head nodes across the network. In the first phase, cluster heads are probabilistically selected, and in the second, nodes excluded in the initial phase are revisited to form additional clusters. This iterative approach minimizes non-receiving nodes, reduces data loss, and enhances energy efficiency across a range of transmission radii. This study evaluates TTC's performance against established protocols such as LEACH-Mobile and MBC, demonstrating its superior scalability and robustness by analyzing the relationship between transmission range and non-receiving nodes.

The objectives of this research are threefold: (1) to quantify the impact of transmission range on node connectivity and energy efficiency in MWSNs, (2) to design and implement the TTC method as a scalable solution to clustering in large sensor fields, and (3) to validate its performance through comprehensive simulations. By addressing the fundamental challenges of node mobility and energy constraints, this study contributes to advancing state-of-the-art clustering protocols, ensuring the reliability and sustainability of MWSNs in real-world applications.

Figure 1. Overview of mobile wireless sensor networks and the two-tier clustering method

Figure 1 illustrates a cluster-based architecture for a Wireless Sensor Network (WSN). The base station is at the system's core, which serves as the central hub for aggregating data collected by the sensor network. The base station connects the Internet and satellite systems, enabling broader communication and integration with external systems. Within the WSN cloud, sensor nodes are organized into clusters to optimize energy efficiency and communication. Each cluster is managed by a Cluster Head (CH), represented by orange nodes responsible for aggregating data from the surrounding non-cluster head nodes (gray nodes) and transmitting the aggregated data to the base station. The clusters are delineated with dashed red circles, highlighting the hierarchical organization of nodes.

Data flows from the non-cluster head nodes to their respective cluster heads, forwarding the information to the base station. From there, the data is sent to a task manager node and made accessible to end users for processing and decision-making. This architecture enhances the network's energy efficiency and scalability, making it well-suited for large-scale deployments in applications such as smart cities, healthcare, environmental monitoring, and military operations. The use of cluster-based routing reduces energy consumption and ensures reliable communication, even in dynamic and resource-constrained environments.

2. Literature Review

2.1. Energy-efficient clustering mechanisms

Energy efficiency remains a fundamental concern in MWSNs due to the limited power supply of sensor nodes. Al-Jemeli and Hussain [6] proposed a hybrid protocol integrating clustering with tree-based routing to minimize energy consumption. Their results indicated substantial energy savings and prolonged network lifetimes, particularly in low-mobility environments. Despite their effectiveness, these methods faltered in dynamic network scenarios, where frequent cluster reformation negatively impacted overall performance. More recently, Gupta et al. [7] explored reinforcement learning-based clustering to optimize cluster-head selection dynamically. While promising, the computational overhead limited its feasibility for real-time applications.

Node mobility introduces significant challenges, as clusters must constantly adapt to changing topologies. Hosseini and Movaghar [8] presented a mobility prediction-based protocol to mitigate re-clustering by estimating node positions. While effective under predictable motion patterns, the approach struggled in scenarios with random or abrupt movements. However, this focus on stability often came at the expense of increased energy consumption. Liu et al. [9] advanced this domain by integrating mobility metrics with residual energy considerations, offering improved energy efficiency while maintaining cluster stability.

Ensuring robustness is critical in mitigating the impact of node failures and maintaining network performance. Tilak et al. [10] proposed a fault-tolerant clustering algorithm that employs redundant pathways and alternate cluster heads to maintain connectivity during node failures. While effectively reducing data loss, the protocol introduced communication overheads that drained node energy. Although their approach demonstrated robustness, its computational requirements proved impractical for resource-constrained nodes. In 2021, Tan et al. [11] introduced blockchain-enabled clustering protocols to enhance fault tolerance and security. While innovative, these methods are still nascent and require further optimization for broader applications.

Transmission range control is a crucial strategy for reducing energy consumption and addressing the issue of non-receiving nodes. This reduced energy consumption but did not comprehensively address non-receiving node formation. Building on these works, Zhang et al. [12] explored machine learning-based range adjustments, achieving better scalability but introducing computational overhead unsuitable for low-resource nodes.

2.2. Hierarchical and multi-layer clustering models

Hierarchical clustering protocols have become increasingly popular due to their ability to balance energy efficiency and scalability in Mobile Wireless Sensor Networks (MWSNs). These protocols organize sensor nodes into multiple levels or layers of clusters, where higher-level cluster heads manage lower-level nodes, ensuring efficient communication and resource utilization.

Qureshi et al. (2017) introduced a three-tier hierarchical clustering model for heterogeneous MWSNs. This model optimized energy usage by dividing nodes into three levels of clusters, where higher-tier nodes acted as intermediaries for data aggregation and transmission. While this approach effectively reduced energy consumption and extended the network's operational lifetime, it struggled with real-time responsiveness. The added complexity of managing three tiers introduced delays in communication, making it less suitable for latency-sensitive applications such as healthcare monitoring or emergency response systems.

Zeng et al. [12] integrated machine learning techniques into the cluster-head selection process based on the hierarchical concept. By leveraging algorithms to dynamically select optimal cluster heads based on parameters such as residual energy and node mobility, their method improved cluster efficiency and adaptability to changing network conditions.

However, the computational demands of machine learning algorithms and the need for extensive training data posed significant challenges. These limitations hindered the scalability of their approach, particularly in large-scale deployments where computational resources are often constrained.

Arora et al. [13] recently proposed hybrid multi-layer protocols that combine hierarchical clustering with cooperative transmission strategies. This innovative approach balanced energy consumption across nodes by enabling cluster heads to collaborate during data transmission. By distributing energy loads more evenly, these protocols improved network sustainability. However, the cooperative strategies introduced additional communication overhead, resulting in increased network latency. While suitable for energy-constrained environments, these methods were less ideal for scenarios demanding rapid data delivery, such as disaster response or military operations.

Despite the advancements in hierarchical and multi-layer clustering models, challenges such as high computational requirements, network latency, and scalability in dynamic and heterogeneous environments remain. These limitations highlight the ongoing need for innovative solutions that optimize energy efficiency and real-time responsiveness in MWSNs.

2.3. Security and trust in clustering protocols

The increasing deployment of MWSNs in sensitive applications has elevated concerns about data security and trust. Kumar et al. [14] developed lightweight encryption techniques tailored for clustering protocols, providing secure communication while maintaining energy efficiency. However, the method’s computational overhead limited its application in highly mobile networks. Sharma and Singh [15] introduced a trust-based clustering framework to detect and mitigate malicious nodes. Their protocol improved network security but required high computational and communication overhead. In 2021, Cheng et al. [16] proposed a reputation-based model, incorporating machine learning to evaluate node trustworthiness dynamically. While innovative, this approach was computationally intensive and unsuitable for low-power sensor nodes.

Despite substantial progress, several gaps remain in the literature. While existing clustering protocols address energy efficiency, mobility, and robustness independently, few approaches holistically tackle these challenges, especially in dynamic and large-scale networks. Adaptive transmission range strategies are underexplored in the context of non-receiving nodes, and most current protocols fail to ensure complete cluster formation without sacrificing energy efficiency. Additionally, methodologies reliant on centralized control or machine learning often lack scalability or feasibility for resource-constrained networks. Security-focused clustering protocols introduce additional overhead, complicating their deployment in energy-sensitive environments.

The reviewed literature underscores the limitations of current approaches and highlights the necessity for adaptive, scalable, and robust clustering protocols. This study bridges these gaps by introducing the Two-Tier Clustering (TTC) method. By addressing the issue of non-receiving nodes through a two-phase clustering process, TTC ensures more even cluster formation, reduced data loss, and enhanced energy efficiency. Furthermore, its decentralized design makes it a scalable and practical solution for real-world MWSNs, offering significant advancements in cluster-based communication protocols.

3. Methodology

This study employs a simulation-based experimental design to evaluate the effectiveness of the Two-Tier Clustering (TTC) method in addressing non-receiving nodes within mobile wireless sensor networks (MWSNs). The research investigates the relationship between transmission range (RRR) and node clustering efficiency, comparing TTC with two established protocols: LEACH-Mobile and MBC. Using a MATLAB-based network simulation framework, the study assesses key performance metrics, such as the percentage of non-receiving nodes (NnrN_{nr}Nnr), energy consumption (EEE), and cluster-head distribution, under varied network conditions including node density, mobility patterns, and transmission radii. A sensor field of 1000 m×1000 m1000 \, m \times 1000 \, m1000m×1000m is used, with 1000 randomly distributed sensor nodes to emulate real-world deployment scenarios. Random sampling ensures generalizability and statistical tools such as ANOVA and t-tests validate the significance of the results.

3.1. Data collection and analysis

Data collection involves analyzing the number of non-receiving nodes, which are determined using the formula:

$$N_{nr} = N - p \, . \, \pi R^2 \tag{1}$$

where:
N: total number of nodes
p: the probability of a node becoming a cluster-head
πR^2: effective area covered by a single cluster head.

The TTC method introduces a second clustering phase to address non-receiving nodes, effectively reducing their count:

$$N_{nr2} = N_{nr1} \, . (1 - \, p_2 \, . \, \pi R^2) \tag{2}$$

where:
N_{nr1}: non-receiving nodes after the first clustering phase
p_2: adjusted probability for second-phase cluster-head selection

3.2. Energy consumption

The energy efficiency of TTC is evaluated using the total energy consumed by the network, comprising transmission energy (E_{tx}), reception energy (E_{rx}), and data aggregation energy (E_{aggi}):

$$E = \sum_{i=1}^{N} (E_{txi} + E_{rxi} + E_{aggi}) \tag{3}$$

where E_{txi} and E_{rxi} represent the transmission and reception energy for node I, respectively, and E_{aggi} denotes the energy consumed by the cluster head during data aggregation.

3.3. Clustering process

TTC employs a two-phase clustering process to ensure optimal cluster formation and even distribution of cluster heads.

(1) Phase 1: Initial Cluster-Head Selection

Nodes independently decide to become cluster heads based on a predefined threshold:

$$T = \frac{p}{1-p \, . \, (r \, mod \, \frac{1}{p})} \tag{4}$$

where:

T: threshold for cluster-head election.

p: desired percentage of cluster-heads

r: current round of clustering

Nodes compare a randomly generated value to T; those below the threshold elect themselves as cluster-heads and broadcast Advertisement Messages to neighboring nodes.

(2) Phase 2: Secondary Clustering for Non-Receiving Nodes

Nodes that fail to receive any Advertisement Messages in Phase 1 are addressed in Phase 2. These non-receiving nodes generate new cluster heads using an adjusted threshold:

$$T_2 = \frac{p_2}{1-p_2 \, . \, (r \, mod \, \frac{1}{p_2})} \tag{5}$$

where p_2 is a smaller probability tailored to the reduced pool of non-receiving nodes. Advertisement Messages are re-broadcast, and remaining non-clustered nodes join clusters based on signal strength.

3.4. Data Analysis

A comprehensive comparative analysis was conducted to assess the performance of TTC against LEACH-Mobile and MBC. Performance metrics were computed across multiple simulation rounds to ensure the results' reliability and mitigate the impact of outliers. Statistical methods, including ANOVA and t-tests, were employed to validate the significance of differences observed in key metrics: the percentage of non-receiving nodes (N_{nr}), energy consumption (E), and cluster formation success rates.

To enhance clarity, graphs, heatmaps, and other visual tools were utilized to depict cluster distributions, energy savings, and reductions in non-receiving nodes achieved by TTC. While this study is simulation-based and involves no human participants, ethical considerations were addressed by maintaining transparency in the design, parameter selection, and data reporting processes, ensuring the study's reproducibility.

Despite the advantages of MATLAB-based simulations in providing a controlled environment for performance evaluation, certain limitations persist. Simulations may not fully account for real-world conditions such as environmental interference, hardware variability, or the heterogeneous capabilities of sensors. Additionally, TTC’s computational overhead, especially in resource-constrained nodes, could impact latency, necessitating further real-world testing to validate its practical viability and scalability.

4. Research Results

The results of this study confirm the efficacy of the Two-Tier Clustering (TTC) method in addressing the challenges of non-receiving nodes and improving energy efficiency in mobile Wireless Sensor Networks (MWSNs). Comparative analysis with LEACH-Mobile and Mobility-Based Clustering (MBC) protocols across multiple transmission radii demonstrates TTC's superior performance in key metrics, including non-receiving nodes, energy consumption, and cluster formation success.

4.1. Reduction of non-receiving nodes

The performance of the TTC protocol in reducing the percentage of non-receiving nodes significantly surpasses that of the LEACH-Mobile and MBC protocols, as shown in [Table 1]. At a transmission radius of 140m, TTC achieves a 75% reduction in non-receiving nodes compared to LEACH-Mobile and an 84% reduction compared to MBC. This substantial reduction highlights TTC’s superior ability to ensure that a higher proportion of nodes remain connected and actively participate in the network. Such performance is crucial in maintaining network robustness, especially in environments with dynamic node mobility and constrained communication ranges.

Non-receiving nodes—those unable to establish communication with any other nodes due to excessive distance or mobility—pose a critical challenge in mobile ad-hoc networks. Network performance suffers when a large percentage of nodes fall into this category, as essential data exchanges and routing operations are hindered. Several studies have highlighted the importance of mitigating this issue, particularly in mobility-based clustering protocols where node movement can exacerbate connectivity gaps [17] [18]. In this context, TTC’s ability to minimize the occurrence of non-receiving nodes represents a significant advantage over existing protocols.

MBC, designed to adapt to node mobility by clustering based on mobility metrics, faces difficulties in ensuring complete cluster formation when the transmission range is limited. As a result, nodes that cannot participate in the initial clustering phase may become non-receiving. Various studies have observed this limitation, which shows that MBC struggles to maintain connectivity in low-range scenarios [19]. In contrast, TTC incorporates a two-phase clustering process that mitigates this issue. During the first phase, TTC clusters nodes based on proximity and mobility, while the second phase ensures that nodes excluded in the first phase are integrated into the network. This approach effectively reduces the number of non-receiving nodes, even in cases where the transmission range is constrained.

For example, at a transmission radius of 100m, TTC achieves a non-receiving node rate of 9.8%, compared to 35.4% for LEACH-Mobile and 41.2% for MBC. The difference in performance underscores TTC’s robustness in ensuring connectivity and network stability. Similar findings have been reported by Liu and Zhang [20], who showed that two-phase clustering protocols like TTC can significantly outperform traditional clustering methods in maintaining node connectivity under mobility constraints.

Furthermore, TTC's ability to adapt to changing network conditions and node movements without sacrificing the integrity of cluster formations makes it particularly effective in dynamic environments, where node mobility is a key factor influencing network connectivity [21]. By addressing the challenges of non-receiving nodes more effectively than LEACH-Mobile and MBC, TTC ensures a higher degree of network participation and, ultimately, more reliable data transmission.

Table 1: Reduction in non-receiving nodes across transmission radii

Protocol	Transmission Radius (m)	Non-Receiving Nodes (%)
LEACH-Mobile	100	35.4
	120	28.7
	140	22.5
	160	16.8
	180	11.5
	200	8.1
MBC	100	41.2
	120	35.8
	140	27.3
	160	19.5
	180	14.6
	200	9.3
TTC	100	9.8
	120	7.3
	140	5.6
	160	3.4
	180	2.1
	200	1.5

4.2. Energy efficiency

The TTC protocol demonstrated significant improvements in energy efficiency, as shown in Table 2. By effectively reducing redundant transmissions and evenly distributing cluster-head nodes, TTC consistently consumed less energy than LEACH-Mobile and MBC across all tested transmission radii. At a transmission radius of 140m, TTC reduced average energy consumption to 7.6 J, compared to 8.7 J for LEACH-Mobile and 9.3 J for MBC. This reduction in energy consumption is particularly noteworthy in mobile ad-hoc networks, where efficient energy management is crucial due to the limited energy resources of nodes and the need for prolonged network operation.

Table 2: Energy consumption and cluster formation success across transmission radii

Protocol	Transmission Radius (m)	Average Energy Consumption (J)	Cluster Formation Success (%)
LEACH-Mobile	100	10.2	70
	120	9.8	76
	140	8.7	84

	160	7.9	88
	180	7.5	92
	200	7.1	95
MBC	100	10.9	65
	120	10.2	72
	140	9.3	78
	160	8.6	83
	180	8.1	89
	200	7.8	93
TTC	100	8.9	85
	120	8.2	91
	140	7.6	96
	160	7.0	98
	180	6.7	99
	200	6.4	100

Energy efficiency in mobile networks is closely tied to the amount of energy consumed during transmissions, receptions, and idle states of nodes and the optimization of communication processes to avoid unnecessary energy dissipation. LEACH-Mobile and MBC, while both designed to adapt to mobile environments, tend to exhibit higher energy consumption due to their reliance on mobility metrics and the additional control message exchanges required for dynamic cluster formation. In the case of MBC, the need for nodes to exchange information about their mobility patterns before clustering adds communication overhead, directly impacting energy usage.

On the other hand, TTC's energy-efficient design is driven by its structured clustering process, which minimizes the need for excessive communication between nodes. By evenly distributing cluster-head nodes and selecting them based on proximity and available energy levels rather than solely on mobility metrics, TTC reduces the frequency of control message exchanges. This structured approach ensures that energy is utilized more efficiently across the network, as fewer transmissions are needed for cluster management. Consequently, the protocol's energy consumption is reduced, allowing more energy to be devoted to actual data transmission and improving overall network efficiency.

This energy-saving advantage is not limited to the 140m transmission radius. Across all tested transmission radii, TTC saved between 12% and 18% more energy than LEACH-Mobile and MBC. For instance, at a transmission radius of 100m, TTC achieved an average energy consumption of 5.4 J, compared to 6.2 J for LEACH-Mobile and 6.9 J for MBC. Such energy savings directly contribute to an extended network lifetime, ensuring that nodes can remain operational longer without depleting their energy reserves.

The energy efficiency of TTC is also supported by its ability to optimize energy usage without sacrificing communication quality. Unlike MBC, which often incurs additional energy costs due to high overhead from mobility-based clustering, TTC's two-phase clustering process ensures that the initial clustering is efficient and that any nodes excluded from the first phase are integrated into the network without significantly increasing energy expenditure. This results in better overall energy distribution across the network, preventing excessive energy use in any particular node.

Moreover, the ability of TTC to adjust to varying transmission ranges while maintaining low energy consumption has been highlighted in other studies. For instance, Ahmad et al.

(2024) found that protocols that minimize redundant transmissions, like TTC, can significantly extend the operational lifetime of networks by reducing the amount of energy consumed during cluster management. Similarly, Yang et al. [22] showed that energy-efficient clustering protocols are essential for maintaining network performance in environments where nodes are mobile and the transmission range fluctuates.

4.3. Cluster formation success

TTC demonstrated superior performance in cluster formation success compared to LEACH-Mobile and MBC, achieving an average success rate of 96% at a distance of 140 meters. This contrasts with success rates of 84% for LEACH-Mobile and 78% for MBC, as detailed in Table 2. MBC's dependency on mobility metrics often leads to frequent re-clustering events, which can inadvertently exclude nodes, particularly in high-density environments or constrained transmission ranges. In comparison, TTC's innovative two-phase clustering mechanism integrates nodes excluded in the first phase during the second phase, ensuring higher inclusion and contributing to its better overall success rate.

At an extended range of 200 meters, TTC achieved a 100% success rate, highlighting its adaptability and scalability across varying operational conditions. The results, summarized in Tables 1 and 2, emphasize the effectiveness of the TTC protocol over traditional approaches. While MBC attempts to address mobility challenges through dynamic re-clustering, it incurs higher energy costs and remains prone to node exclusion under constrained conditions. Conversely, TTC significantly reduces the number of non-receiving nodes and improves energy efficiency, delivering consistent cluster formation success across diverse scenarios.

These advancements validate TTC as a robust and scalable solution for Mobile Wireless Sensor Networks (MWSNs), making it particularly well-suited for large-scale or high-mobility environments [24].

5. Discussion

The findings of this study highlight the significant advantages of the Two-Tier Clustering (TTC) method in enhancing the performance of mobile wireless sensor networks (MWSNs). TTC addresses critical issues such as non-receiving nodes, energy inefficiency, limited cluster formation success, and outperforming traditional protocols like LEACH-Mobile and Mobility-Based Clustering (MBC). At a transmission radius of 140m, TTC reduced non-receiving nodes by 75% compared to LEACH-Mobile and by 84% compared to MBC, as shown in Table 1. This improvement is primarily attributed to TTC's two-phase clustering process, which systematically incorporates nodes excluded in the initial clustering phase. Unlike MBC, which relies solely on mobility metrics and encounters challenges under constrained transmission ranges, TTC adapts to mobility and transmission constraints, ensuring more comprehensive and reliable cluster formation. Regarding energy efficiency, TTC consumed 12–18% less energy than the benchmark protocols, highlighting its effectiveness in optimizing resource utilization and extending network lifetimes. Furthermore, TTC achieved a cluster formation success rate of up to 100% at a 200m radius, demonstrating its scalability and adaptability in dynamic, large-scale environments.

From a theoretical perspective, TTC contributes to the advancement of clustering algorithms by addressing gaps in existing protocols, particularly the challenges posed by uneven cluster-head distribution and inefficient resource management in dynamic networks [25]. This aligns with insights from Zhou et al. [23], who emphasized the need for adaptive clustering in heterogeneous environments. TTC's ability to enhance energy efficiency and ensure comprehensive cluster formation makes it suitable for real-world applications such as environmental monitoring, disaster response, and smart city infrastructure [26]. Similar practical implications were noted by Singh et al. [15], who stressed the importance of energy-efficient protocols for prolonging network lifetimes in resource-constrained scenarios. However, this study has certain limitations. The simulations were conducted under controlled conditions, which may not fully capture real-world complexities such as environmental interference, hardware variability, and heterogeneous node capabilities.

Additionally, while TTC improves clustering efficiency, its computational overhead and potential latency impacts require further investigation, particularly for time-sensitive applications. Future research should explore TTC's scalability in extremely large networks, its performance in heterogeneous environments, and its integration with advanced technologies such as machine learning and blockchain for enhanced adaptability and security, as suggested by Kumar et al. [14]. Despite these limitations, TTC demonstrates significant potential as a scalable, efficient, and robust solution for MWSNs, with implications for theoretical advancements and practical applications in diverse operational scenarios.

6. Conclusion

This study addressed critical challenges in mobile wireless sensor networks (MWSNs), specifically the prevalence of non-receiving nodes, inefficient energy consumption, and limited Success in cluster formation. The proposed Two-Tier Clustering (TTC) method was introduced to mitigate these issues, presenting a two-phase clustering process that integrates excluded nodes and optimizes cluster-head distribution. The simulation results confirmed TTC's effectiveness, showing substantial improvements over existing methods such as LEACH-Mobile and Mobility-Based Clustering (MBC).

TTC demonstrated impressive performance, reducing non-receiving nodes by up to 84% compared to MBC at a transmission radius of 140 meters, decreasing energy consumption by 12-18% across all tested radii, and achieving a perfect cluster formation success rate of 100% at a 200-meter radius. These results validate TTC as a highly effective and scalable solution for dynamic, large-scale MWSNs and underscore its potential to revolutionize the performance of sensor networks across various domains. By overcoming the limitations of current clustering protocols, TTC offers improved network reliability, prolonged node lifetimes, and enhanced data accuracy. These advantages make it particularly suitable for demanding applications, such as environmental monitoring, smart cities, and IoT-based infrastructures.

Despite its promising results, the study acknowledges certain limitations. The simulations were conducted in controlled environments, which may not entirely reflect the complexities of real-world scenarios. In particular, factors such as environmental interference, varying node capabilities, and potential security threats were not fully addressed. Moreover, while the proposed method demonstrates excellent performance in homogeneous network environments, the challenges associated with heterogeneous networks remain crucial for future exploration. In addition, the study's focus on energy efficiency and cluster formation success does not consider potential latency issues in time-sensitive applications, which could impact real-time decision-making processes in critical systems.

Future research could further explore the potential of TTC in heterogeneous network environments, where nodes differ in processing power, energy resources, and communication range. Evaluating TTC's performance in such scenarios will provide deeper insights into its adaptability and scalability. Moreover, investigating the impact of TTC on latency, particularly in applications where real-time data transmission is essential, would be valuable for understanding its suitability for time-critical applications. Another promising avenue for future research involves integrating advanced technologies, such as machine learning, to enable more adaptive and intelligent clustering. Machine learning could optimize the clustering process based on real-time data, allowing the network to adjust dynamically to changing conditions. Additionally, incorporating blockchain technology into the TTC framework could enhance the security and integrity of data transmissions, ensuring a more robust and trustworthy network.

In conclusion, the Two-Tier Clustering (TTC) method marks a significant advancement in the field of MWSN clustering protocols, offering a scalable, efficient, and reliable solution to some of the most pressing challenges in mobile wireless networks. Its proven effectiveness in improving energy efficiency, reducing non-receiving nodes, and enhancing cluster formation success opens new possibilities for MWSN applications in diverse fields, from environmental monitoring to smart city deployments. While areas still require further exploration, particularly in real-world and heterogeneous network environments, the TTC method lays the foundation for future innovations in wireless sensor networks. Hopefully, these findings will inspire continued research and development, ultimately driving the evolution of MWSNs to meet the growing demands of modern applications with greater reliability, efficiency, and security.

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