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Optimizing Node Distribution Strategies for Prolonged Lifetime in Wireless Sensor Networks: A Comprehensive Review

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Abstract: Wireless Sensor Networks (WSNs) have become indispensable in diverse applications such as environmental monitoring, military surveillance, and smart agriculture. However, their utility is often constrained by limited energy resources of sensor nodes, making network lifetime a critical performance metric. Among the various strategies proposed to enhance the longevity of WSNs, optimizing node distribution has proven particularly effective. This paper provides a comprehensive review of node distribution techniques aimed at maximizing WSN lifetime. It analyzes deterministic and stochastic deployment models, load-balancing mechanisms, coverage-aware strategies, and clustering-based approaches. The paper also evaluates the performance implications of these methods in terms of energy consumption, scalability, and fault tolerance. Finally, the study identifies open research challenges and proposes future research directions for sustainable and energy-efficient WSN design.

Keywords: Wireless Sensor Networks (WSNs), Network Lifetime, Node Distribution, Energy Efficiency, Deployment Strategies, Coverage Optimization, Clustering, Topology Control, Load Balancing, Routing Protocols

1. Introduction

Wireless Sensor Networks (WSNs) consist of spatially distributed autonomous sensors that cooperatively monitor physical or environmental conditions. One of the fundamental limitations of WSNs is the finite battery life of sensor nodes. Once deployed, recharging or replacing batteries is often impractical, especially in inaccessible environments. Consequently, extending the network lifetime has become a primary design goal. Node distribution plays a pivotal role in determining the energy efficiency and operational longevity of a WSN. Improper deployment can lead to energy holes, coverage gaps, and uneven load distribution, ultimately reducing the network's effective lifetime. This paper surveys and critically analyzes various node distribution strategies that enhance WSN lifetime.

In direct communication protocol, each sensor node sends its data directly to the base station. Direct communication will require a large amount of transmit power from each node if the base station is far. The second conventional approaches we consider is a “minimum-energy” routing protocol. In this protocol, nodes route data through intermediate nodes ultimately destined for the base station. Thus every node acts as a router for other nodes in addition to sensing the environment. These protocols differ in the way the routes are chosen.

We can divide cluster based routing protocols mainly in two parts, Protocols for homogeneous environment and protocols for heterogeneous environment. LEACH is one of the first cluster based routing protocol. It assigns equal probability for each node to become cluster head. This works well for the homogeneous networks but not for the heterogeneous networks because of the unequal energy of nodes. SEP prolongs the lifetime of WSNs by inserting a percentage of heterogeneous nodes. Heterogeneous WSNs consist of sensor nodes with different ability, such as different sensing range and data computing power. By adding these nodes we can follow different cluster selection scheme. This will give higher stability to the cluster and longer time to survive the cluster. This scheme depends on current node energy; each node will be CH depending on its remaining energy. Another problem occurs in handling the huge amount of information and to pass it over through every node of the network. To resolve this issue, we need to have an efficient routing protocol that has low routing overhead and a good data aggregation technique to save the limited power of sensing node. By introducing the SEA LEACH(Special Energy Activated Low energy adaptive cluster head) [3], we are trying to improve lifetime of the LEACH protocol in homogeneous and heterogeneous mediums. It focuses on less power consumption for data aggregation by using threshold value concept. We are going to use distributed sensor nodes using dynamic cluster head rotation. SEA LEACH can be divided into two parts: Phase-1 and Phase-2. Initially we are assuming that all the sensor nodes are at same energy level so that we can consider the system to be homogeneous. When some of the nodes die, system becomes unstable and homogeneous routing protocols are not able to take the advantage of remaining energy. After some time, the energy levels will be different among the nodes and hence the field can be assumed as heterogeneous system. We also assume that, all the nodes are steady.

2. Background and Motivation

2.1. WSN Architecture and Lifetime Metrics

A typical WSN includes sensor nodes, a sink node (or base station), and communication protocols. The lifetime of a WSN is often defined in terms of:

- First node death (FND)

- Half node death (HND)
- Network partitioning time
- Coverage preservation duration

2.2. Role of Node Distribution

Node distribution directly impacts communication overhead, data aggregation efficiency, and energy consumption. Two main strategies exist:

Deterministic Deployment: Nodes are placed manually or with predefined coordinates.
Random Deployment: Nodes are dropped randomly, often used in hostile or inaccessible environments.

3. Challenges in Node Distribution for WSNs

- Energy Imbalance: Uneven node density leads to hotspot formation and rapid energy depletion.
- Coverage Redundancy or Holes: Overlapping sensing areas waste energy, while gaps reduce monitoring effectiveness.
- Load Imbalance: Nodes near the sink handle more traffic, leading to faster energy exhaustion.
- Scalability Issues: Efficient node distribution becomes more complex as network size increases.

4. Node Distribution Techniques for Lifetime Enhancement

4.1. Deterministic Deployment Techniques

Grid-based Deployment: Nodes are placed in a structured grid pattern to ensure uniform coverage.
Hexagonal and Triangular Tessellation: Inspired by cellular networks, these patterns optimize coverage and connectivity.
Optimization Algorithms: Use of Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) to find optimal node placement.

4.2. Random Deployment with Post-deployment Adjustment

Virtual Force Algorithm (VFA): Nodes self-adjust their positions using attractive or repulsive forces to balance coverage.
Swarm Intelligence Techniques: Algorithms like Artificial Bee Colony (ABC) and PSO are used post-deployment to relocate nodes.

4.3. Clustering-Based Distribution

LEACH and HEED Protocols: Cluster-head selection balances energy consumption among nodes.
Unequal Clustering: Clusters closer to the sink are smaller to reduce load imbalance.

4.4. Coverage and Connectivity Preservation

Sensing Coverage Models: Ensure full area monitoring with the minimum number of active nodes.
Connectivity-aware Distribution: Maintains communication paths while conserving node energy.

5. Related Work:

The enhancement of network lifetime in Wireless Sensor Networks (WSNs) through optimal node distribution has attracted considerable attention in recent years. Various researchers have explored diverse deployment models, clustering strategies, and optimization techniques aimed at balancing energy consumption across the network. This review highlights significant contributions made by different authors in the field, discussing how node distribution directly influences WSN longevity.

Younis and Fahmy (2004) introduced the HEED (Hybrid Energy-Efficient Distributed) clustering protocol, which became a foundational work in the clustering-based approach to prolonging WSN lifetime. Their method selects cluster heads based on residual energy and intra-cluster communication cost, leading to more balanced energy consumption across nodes. Similarly, Heinzelman et al. (2000) developed the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol, one of the earliest techniques to address energy efficiency via node clustering. LEACH randomly rotates cluster heads to evenly distribute energy usage, thereby delaying the death of individual nodes and improving overall network lifespan.

Akyildiz et al. (2002) provided a comprehensive overview of WSN architecture and energy constraints, emphasizing the critical role of node deployment strategies. Their work laid the groundwork for understanding how node placement affects connectivity, coverage, and energy consumption. Following this, Wang et al. (2005) proposed a node deployment strategy based on energy-aware coverage, using a probabilistic sensing model to maintain adequate monitoring with fewer active nodes. Their approach was particularly efficient in conserving energy by allowing redundant nodes to enter sleep mode.

In terms of deterministic deployment, Meguerdichian et al. (2001) explored worst-case coverage and identified regions in the sensing field where coverage was weakest. This analysis led to strategic node placement techniques aimed at reinforcing weak areas to prevent energy hotspots. Howard, Mataric, and Sukhatme (2002) further developed mobile robot-based deployment, where sensor nodes autonomously moved to optimal locations based on a virtual force algorithm. This distributed method improved both coverage and connectivity while balancing energy use.

More recent studies have focused on applying metaheuristic optimization algorithms for node distribution. Yoon and Kim (2013) utilized Genetic Algorithms (GA) to determine optimal node placement that maximizes network coverage while minimizing the number of nodes required. Their results demonstrated significant energy savings through efficient placement. Likewise, Liu et al. (2012) implemented Particle Swarm Optimization (PSO) to optimize node distribution for uniform coverage, showing that evolutionary algorithms are effective in large-scale sensor fields where manual deployment is infeasible.

Bourennane et al. (2019) investigated heterogeneous node deployment by placing high-energy nodes in high-traffic areas, especially around the sink, to prevent early node death due to excessive data transmission. Their work highlights the significance of role-aware deployment in avoiding energy holes and extending the overall network lifetime. Similarly, Pan, Fang, and Wang (2014) proposed an unequal clustering mechanism where cluster sizes were inversely proportional to their distance from the sink, effectively addressing the energy hole problem common in uniform clustering methods.

In the context of 3D WSNs, which are crucial for underwater and environmental monitoring, authors like Cheng et al. (2017) proposed three-dimensional node distribution strategies that take terrain and spatial constraints into account. These methods used modified PSO and grid-based schemes to ensure uniform sensing while minimizing energy waste due to unnecessary communication overhead.

Swarm intelligence has also gained prominence in recent research. Li et al. (2015) introduced an Ant Colony Optimization (ACO)-based approach for node relocation, dynamically adjusting positions based on local energy levels and coverage metrics. Their algorithm enabled self-healing networks with adaptive topologies, significantly extending WSN longevity without centralized control.

In conclusion, the literature clearly demonstrates that node distribution is a pivotal factor in extending WSN lifetime. While traditional methods like LEACH and HEED offer simplicity and scalability, modern optimization-based and hybrid approaches present superior performance in dynamic and large-scale deployments. Each method contributes uniquely, from deterministic layouts and clustering to swarm intelligence and 3D adaptations. Future research must continue to build on these findings, integrating artificial intelligence and real-time adaptability to create self-sustaining and energy-aware WSNs suitable for emerging IoT applications.

Heinzelman, et.al. [10] proposed LEACH-centralized (LEACH-C), a protocol that uses a centralized clustering algorithm and the same steady-state protocol as LEACH.

O. Younis, et.al [1] proposed HEED (Hybrid Energy-Efficient Distributed clustering), which periodically select cluster heads according to a hybrid of the node residual energy and a secondary parameter, such as node proximity to its neighbors or node degree.

T. N. Qureshi et. al., [2] Wireless Sensor Networks (WSNs) contain numerous sensor nodes having limited power resource, which report sensed data to the Base Station (BS) that requires high energy usage. Many routing protocols have been proposed in this regard achieving energy efficiency in heterogeneous scenarios. However, every protocol is not suitable for heterogeneous WSNs. Efficiency of protocol degrades while changing the heterogeneity parameters. In this paper, we first test Distributed Energy- Efficient Clustering (DEEC), Developed DEEC (DDEEC), Enhanced DEEC (EDEEC) and Threshold DEEC (TDEEC) under several different scenarios containing high level heterogeneity to low level heterogeneity. We observe thoroughly regarding the performance based on stability period, network life time and throughput. EDEEC and TDEEC perform better in all heterogeneous scenarios containing variable heterogeneity in terms of life time, however TDEEC is best of all for the stability period of the network. However, the performance of DEEC and DDEEC is highly effected by changing the heterogeneity parameters of the network.

G. Smaragdakis, I. Matta, A. Bestavros proposed SEP (Stable Election Protocol) [9] in which every sensor node in a heterogeneous two-level hierarchical network independently elects itself as a cluster head based on its initial energy relative to that of other nodes.

Li Qing et.al. [11] Proposed DEEC (Distributed energy efficient Clustering) algorithm in which cluster head is selected on the basis of probability of ratio of residual energy and average energy of the network. Simulations show that its performance is better than other protocols.

Md. Solaiman Ali, et.al [4] proposed ALEACH (Advanced LEACH) a new technique to select the cluster heads in every round which depends both on current state probability and general probability.

Sajjanhar et al. [5] proposed a Distributive Energy Efficient Adaptive Clustering (DEEAC) Protocol, which is having spatio-temporal variations in data reporting rates across different regions. DEEAC selects a node to be a cluster head depending upon its hotness value and residual energy.

B. Elbhiri et al [6], proposed SDEEC (Stochastic Distributed Energy-Efficient Clustering (SDEEC) SDEEC introduces a balanced and dynamic method where the cluster head election probability is more efficient. Moreover, it uses a stochastic scheme detection to extend the network lifetime. Simulation results show that this protocol performs better than the Stable Election Protocol (SEP) and the Distributed Energy- Efficient Clustering (DEEC) in terms of network lifetime.

Inbo Sim, et.al [7] proposed ECS (Energy efficient Cluster header Selection) algorithm which selects CH by utilizing only its information to extend network lifetime and minimize additional overheads in energy limited sensor networks.

Ma Chaw Mon Thein, et.al [8] proposed a modification of the LEACH's stochastic cluster-head selection algorithm by considering the additional parameters, the residual energy of a node relative to the residual energy of the network for adapting clusters and rotating cluster head positions to evenly distribute the energy load among all the nodes. We have proposed an approach called threshold distributed energy efficient clustering (TDEEC) algorithm whose main aim is to increase the energy efficiency and stability of the heterogeneous wireless sensor networks.

6. Comparative Analysis

Technique	**Energy Efficiency**	**Coverage**	**Scalability**	**Complexity**	**Adaptability**
Grid-based	Moderate	High	Low	Low	Low

Technique	Energy Efficiency	Coverage	Scalability	Complexity	Adaptability
Optimization-based	High	High	Moderate	High	High
Clustering (LEACH, HEED)	High	Moderate	High	Moderate	Moderate
VFA	Moderate	High	High	Moderate	High
Swarm Intelligence	High	High	Moderate	High	High

7. Future Research Directions

- Energy-Aware AI Deployment Models: Integrating deep learning and reinforcement learning for predictive node placement.
- 3D Node Distribution: Applications in underwater or aerial WSNs require sophisticated 3D deployment strategies.
- Mobile Sensor Networks: Dynamic redistribution based on network feedback can further extend lifetime.
- Cross-layer Optimization: Combining distribution strategies with routing and MAC layer adjustments.

8. Conclusion

Enhancing WSN lifetime through effective node distribution is a multifaceted challenge that necessitates a balance between coverage, connectivity, and energy efficiency. This review has examined a variety of techniques including deterministic placement, clustering, and intelligent relocation strategies. While each method has its strengths and limitations, hybrid approaches and intelligent optimization models appear most promising. Future research must focus on scalable, adaptive, and autonomous distribution methods that are robust to real-world deployment constraints.

References:

[1] O. Younis, S. Fahmy, HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks, IEEE Transactions on Mobile Computing 3 (4) (2004) 660–669.
[2]. T. N. Qureshi, N. Javaid, M. Malik, U. Qasim, Z. A. Khan, "On Performance Evaluation of Variants of DEEC in WSNs".
[3] M. Naseem et. al., " Energy Efficient Routing Protocol in Wireless Sensor Network" International Journal of Research and Development in Applied Science and Engineering, Volume 1, Issue 1, May 2015
[4] Md. Solaiman Ali, Tanay Dey, and Rahul Biswas, ―ALEACH: Advanced LEACH Routing Protocol for Wireless Microsensor Networks‖ ICECE 2008, 20-22 December 2008.
[5] U. Sajjanhar, P. Mitra, ―Distributive Energy Efficient Adaptive Clustering Protocol for Wireless Sensor Networks‖, Proceedings of the 2007 International Conference on Mobile Data Management, pp. 326 - 330, 2007.
[6] Elbhiri Brahim,Saadane Rachid,Alba-Pages Zamora, Driss Aboutajdine, ―Stochastic Distributed Energy-Efficient Clustering (SDEEC) for heterogeneous wireless sensor networks‖, ICGST-CNIR Journal, Volume 9, Issue 2, December 2009.
[7] Inbo Sim, KoungJin Choi, KoungJin Kwon and Jaiyong Lee, ―Energy Efficient Cluster header Selection Algorithm in WSN‖, International Conference on Complex, Intelligent and
Software Intensive Systems , IEEE, 2009.
[8] Ma Chaw Mon Thein, Thandar Thein ―An Energy Efficient Cluster-Head Selection for Wireless Sensor Networks‖, International Conference on Intelligent Systems, Modeling and Simulation, IEEE 2009.
[9] G. Smaragdakis, I. Matta, A. Bestavros, SEP: A Stable Election Protocol for clustered heterogeneous wireless sensor networks, in: Second International Workshop on Sensor and Actor Network Protocols and Applications (SANPA 2004), 2004.
[10] W.R. Heinzelman, A.P. Chandrakasan, H. Balakrishnan, An application- specific protocol architecture for wireless microsensor networks, IEEE Transactions on Wireless Communications 1 (4) (2002) 660–670.
[11] L. Qing, Q. Zhu, M. Wang, "Design of a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks". ELSEVIER, Computer Communications 29, 2006, pp 2230- 2237.
[12] O. Younis, S. Fahmy, HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks, IEEE Transactions on Mobile Computing 3 (4) (2004) 660–669.
[13] S. Bandyopadhyay, E.J. Coyle, An energy efficient hierarchical clustering algorithm for wireless sensor networks, in: Proceeding of INFOCOM 2003, April 2003.
[14] V. Mhatre, C. Rosenberg, Design guidelines for wireless sensor networks: communication, clustering and aggregation, Ad Hoc Network Journal 2 (1) (2004) 45–63.
[15] M. Ye, C. Li, G. Chen, J. Wu, EECS: an energy efficient cluster scheme in wireless sensor networks, in: IEEE International Workshop on Strategies for Energy Efficiency in Ad Hoc and Sensor Networks (IEEE IWSEEASN2005), Phoenix, Arizona, April 7–9, 2005.
[16] Anurag et. al., "Load Forecasting by using ANFIS", International Journal of Research and Development in Applied Science and Engineering, Volume 20, Issue 1, 2020
[17] Raghawend, Anurag, "Detect Skin Defects by Modern Image Segmentation Approach, Volume 20, Issue 1, 2020
[18] D. Estrin, R. Govindan, J. Heidemann, S. Kumar, Next century challenges: scalable coordination in sensor networks, in: Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'99), August 1999, pp. 263–270.
[19] L. Qing, Q. Zhu, M. Wang, "Design of a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks". ELSEVIER, Computer Communications 29, 2006, pp 2230- 2237.
[20] A. Manjeshwar and D. P. Agarwal, "TEEN: a routing protocol for enhanced efficiency in wireless sensor networks," In 1st International Workshop on Parallel and

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Distributed Computing Issues in Wireless Networks and Mobile Computing, April 2001.
[21] A. Manjeshwar and D. P. Agarwal, "APTEEN: A hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks," Parallel and Distributed Processing Symposium., Proceedings International, IPDPS 2002, pp. 195-202.
[22] Elbhiri, B. , Saadane, R. , El Fkihi, S. , Aboutajdine, D. "Developed Distributed Energy-Efficient Clustering (DDEEC) for heterogeneous wireless sensor networks", in: 5th International Symposium on I/V Communications and Mobile Network (ISVC), 2010.
[23] Parul Saini, Ajay.K.Sharma, "E-DEEC- Enhanced Distributed Energy Efficient Clustering Scheme for heterogeneous WSN", in: 2010 1st International Conference on Parallel, Distributed and Grid Computing (PDGC - 2010).
[24] Md. Solaiman Ali, Tanay Dey, and Rahul Biswas, ―ALEACH: Advanced LEACH Routing Protocol for Wireless Microsensor Networks‖ ICECE 2008, 20-22 December 2008.