JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A Comprehensive Review on Coverage Optimization of Wireless Sensor Networks (WSNs)

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Abstract: In now a day wireless sensor networks (WSN) are used in various fields. For example, in the field of agriculture, healthcare, industrial automation, environmental monitoring and smart cities. There are various factors which defines the performance of WSN, some of them are coverage, connectivity, over-coverage and energy consumption etc. Now from these parameters coverage is an essential parameter of WSN which tells us that how well the area is covered. There are also some parameters which effects the coverage of WSN like sensor range, sensor lifespan, number of sensors, communication range. This paper offers a thorough examination of algorithms or methods used on WSN to enhance their coverage. We study different types of methods and algorithms like max, area strategy, geometric centroid of Voronoi diagram, particle swarm algorithm (PSO), harmony search algorithm (HSA), arrow search optimization algorithm (SSA), Harris hawk algorithm (HHA), ant army search optimization algorithm (AASO), adaptive Cauchy variant butterfly optimization algorithm (ACBOA) and many more.

Keywords Wireless sensor networks (WSN), coverage, optimization algorithms.

I. INTRODUCTION

The WSN are used to observe the conditions like temperature, pressure, motion, sound, vibration, soil moisture and pollutants and after observing the data of the location where they are placed the send this data to the base station.

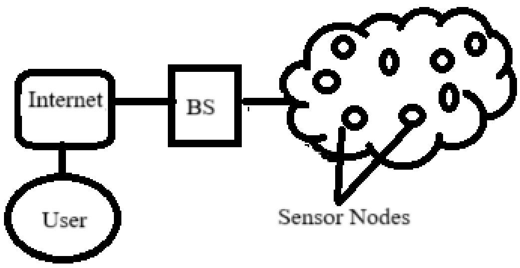

figure 1: architecture of WSN

Wireless Sensor Networks (WSNs) consist of distributed sensor nodes equipped with wireless communication capabilities, designed to monitor and collect data from specific physical environments [1]. These networks have become increasingly relevant in applications such as forest fire detection, water and soil monitoring, and other critical environmental assessments. A fundamental design challenge in WSNs is balancing coverage—ensuring that sensor readings adequately represent the monitored region—and network lifetime, which is constrained by the limited battery capacity of sensor nodes [1].
One of the central issues in WSN operation is the trade-off between sensor coverage and energy consumption. Ensuring continuous and high-quality coverage typically requires more sensors to remain active, which accelerates energy depletion and reduces the network's operational duration. Conversely, conserving energy by putting sensors into sleep mode can compromise coverage quality. This trade-off becomes more complex in dynamic scenarios where the network's mission can change, as in military surveillance tasks that unexpectedly extend in duration. Since deploying additional nodes mid-operation is often not feasible, dynamic scheduling and coverage adjustment become necessary strategies [2].
The increasing deployment of WSNs across diverse sectors has brought attention to the need for more intelligent and sustainable network designs. These networks rely on small, self-organizing sensor nodes that are capable of sensing, processing, and wirelessly transmitting data. Given that replacing batteries in remote or hostile environments is either impractical or impossible, developing approaches that extend network lifespan by improving coverage efficiency and minimizing energy usage has become a major research focus [3].

With advancements in microelectromechanical systems (MEMS), WSNs have gained rapid traction as viable tools for environmental sensing. However, to fully exploit their potential, several foundational problems must be addressed—particularly sensor placement, which determines how effectively the network can monitor its environment. This challenge is closely related to the broader task of optimizing various sensor parameters, and it directly impacts how well the network can perform key functions such as localization, tracking, and data aggregation [4].

WSNs have emerged as a backbone technology for the development of smart environments. Originally conceived for military uses like battlefield surveillance, these networks have evolved to serve numerous industrial and consumer applications. Among the most pressing technical concerns is the deployment strategy—specifically, how to achieve maximum coverage with minimal sensor deployment. Since sensor coverage serves as a core metric for detection accuracy and surveillance quality, a variety of heuristic-based approaches have been explored to optimize sensor placement and coverage [5].

II. LITRETURE REVIEW

Wireless Sensor Networks (WSNs) face critical challenges concerning sensor coverage, energy efficiency, node placement, and connectivity. Numerous algorithms and models have been proposed over the years to enhance the performance of WSNs in these areas. This literature review presents a comprehensive conceptual grouping of significant studies addressing these challenges.

Firstly, [1] presents an analytical framework to assess the coverage and lifespan of a WSN characterized by a 2D Gaussian distribution. The paper also explore how coverage and lifespan are affected when the Gaussian dispersion dimensions have differing Gaussian parameters. Based on their findings, they propose sensor deployment strategies aimed at achieving targeted coverage and lifespan. Then demonstration employ that a Gaussian distribution can significantly enhance the network's lifespan. The analytical findings provide valuable guidelines for WSN design. Building on coverage optimization, [2] investigates how to schedule sensor activity to optimize coverage within a defined network lifetime. Unlike traditional sensor deployment aimed at maximizing spatial coverage, their focus is on enhancing spatiotemporal coverage through the scheduling of sensors post-deployment. The paper proposes a distributed parallel optimization protocol (POP), where nodes autonomously optimize their schedules while achieving local optimality without conflicts. Simulation results show that POP significantly outperforms other methods in terms of network lifetime, coverage redundancy, convergence time, and event detection probability.

Expanding on optimization methods, [3] proposes an optimization strategy that integrates Cellular Automation (CA) principles with GA. The findings indicate that, for a target area with complex boundaries, a WSN can achieve optimal coverage from an initially random configuration through self-organized adjustments and power management. Additionally, simulation results demonstrate that the CGA outperforms traditional GA and Efficient Cover Set Selection (ECSS) methods in optimizing coverage. In contrast to deterministic approaches, [4] introduces a probabilistic sensor model aimed at optimizing sensor placement. The paper implement various optimization techniques for sensor placement, suggesting future research may involve evolutionary multi-objective optimization to address multiple criteria simultaneously, including the number of sensors, energy efficiency, and diverse coverage.

Pursuing further improvements, [5] presents a deterministic sensor deployment method utilizing wavelet transform (WT) to maximize coverage quality in wireless sensor networks (WSNs) while minimizing the number of sensors deployed on a 3-D surface. A key innovation of this work is the use of a modified CSO algorithm, which mimics cat behavior, adapted specifically for sensor deployment on 3-D terrains. The performance of proposed CSO-based sensor deployment method with Delaunay Triangulation and Genetic Algorithm approaches, and results demonstrate its superiority. From another probabilistic angle, [6] transforms the problem of probabilistic area coverage into one of probabilistic point coverage, effectively reducing the problem’s complexity. Then paper introduce the ε-FCO algorithm and the simulation results confirm that the ε-FCO algorithm not only ensures comprehensive ε-full area coverage but also surpasses other probabilistic coverage protocols. Further addressing hybrid challenges, [7] introduces a Hy-MFCO designed to manage sensing coverage and network lifetime. The framework consists of two main components: a memetic algorithm (MA)-based scheduling strategy and a heuristic recursive algorithm (HRA). Simulation results reveal that Hy-MFCO excels in preserving sensing coverage and extending network lifetime.

To structure sensor scheduling, [8] introduces novel methods for optimizing connected coverage through a virtual hexagon partition composed of hexagonal cells. They paper proposes the Three-Symmetrical Area Method (3-Sym), followed by the Symmetrical Area Optimization Method (O-Sym), which minimizes active sensors while maximizing efficiency. Addressing energy-efficient communication, [9] investigates green communication within 3D directional sensor networks, using a 3D sensing model. The paper introduces a grid-based and position-based algorithms, and the STCOS algorithm effectively enhances spatial-temporal coverage optimization. Meanwhile, [10] introduces a demand-based routing protocol that preserves both coverage and connectivity while reducing energy usage through dynamic sensing range assignment and sensor radio scheduling. Simulation results confirm the protocol's effectiveness. Then [11] focuses on distributed coordination algorithms to enhance coverage in mobile sensor networks. Operating iteratively and using local information, these algorithms reduce coverage holes, as confirmed by simulations.

Enhancing mobility strategies, [12] presents a Voronoi-based strategy where each sensor is repositioned within its Voronoi cell using a coverage improvement scheme called Max-Area. This approach leads to a monotonic increase in overall weighted coverage. Then [13] proposes the HSA algorithm to determine the optimal number and placement of sensor nodes. The objective function ensures coverage while reducing cost and node count, achieving 100% coverage in some cases. Extending Voronoi applications, [14] presents GCVD, which enables safe node movement to ensure maximum area coverage and minimal energy consumption. Results show it outperforms existing algorithms. For further improvement, [15] applies an enhanced particle swarm optimization algorithm to maximize WSN coverage, showing better performance than standard PSO.

In a nature-inspired approach, [16] proposes a strategy based on the Vampire Bat Optimization (VBO), improving energy balance among nodes and outperforming several other algorithms. Continuing with bio-inspired methods, [17] uses an improved AFSA for coverage optimization. The proposed method reduces energy consumption while maintaining coverage and convergence speed.

In terms of multi-objective strategies, [18] utilizes a genetic algorithm combined with the weighted sum method (MOONGA) for node placement, showing effective results across various conditions. Then for obstacle rich environments [19] introduces BISON, a Voronoi-based method for rapid deployment. It achieves fast, maximum coverage while considering environmental noise. Taking a novel optimization approach, [20] employs an enhanced SSO algorithm called CSSO, using chaotic initialization to optimize sensor placement in HWSNs. This method addresses gaps and redundancy. Following this, [21] proposes the AASO optimizer, based on army ant behavior, which shows strong performance in exploration and exploitation. From meta-heuristic algorithms [22] utilizes a meta-heuristic HHO algorithm to identify optimal node locations using a probabilistic sensing model, outperforming PSO in terms of stability and convergence.

To improve soil moisture WSNs, [23] develops an ACBOA using adaptive Cauchy variants. The algorithm increases coverage rates significantly compared to other optimization techniques. Then for localization [24] enhances the DV-Hop localization algorithm using an improved SSA, correcting errors through deviation correction and minimum MSE, resulting in better localization accuracy. Finally, [25] proposes MOFAC-GAPSO, a hybrid algorithm aimed at maximizing coverage area while reducing energy consumption and coverage holes. Compared to existing techniques, it achieves full area coverage with just 25 sensor nodes.

Table 1: - Comparison of various Coverage Optimization Methods and Algorithms

Author Name	Journal (Year)	Algorithm Name	Input Parameters	Output parameters
Demin Wang et al	IEEE (2008)	Gaussian Distribution	Area = 100×80 ellipse Number of nodes = 999 Sensing range = 10m Communication range = 20m.	Coverage = 97.14%
Li Xunbo & Wang Zhenlin	Chinese Journal of Electronics (2011)	Cellular Genetic Algorithm	Area = 50×50 m^2 Number of nodes = 40 Sensing Range = 9m.	Coverage = 98.6%
Hari Prabhat Gupta & S.V. Rao	IEEE (2014)	Coverage & Connectivity Preserving Routing Protocol	Area = 200×200 m^2 Number of nodes = 200 Sensing range = 18m.	Coverage = 99%
Hamid Mahboubi et al	IEEE (2016)	Distributed Coordination Algorithms	Area = 50×50 m^2 Number of nodes = 27, 15 nodes with 6m, 6 nodes with 5m, 3nodes with 7m, and 3 nodes with 9m of sensing range.	Coverage = 99%
Osama Moh'd Alia and Alaa Al-Ajouri	IEEE (2017)	Harmony Search Algorithm	Area = 50×50 m^2 Number of nodes = 25 Sensing range = 10m Cell size = 10×10	Coverage = 100%
Jalal Habibi et al	IEEE (2017)	Max, Area Strategy	Area = 15×15 m^2 Number of nodes = 50 Sensing range = 4m Communication range = 25m.	Coverage = 97.9%
Tongxin Shu et al	IEEE (2019)	Geometric Centroid of Voronoi Diagram	Area = 50×50 m^2 Number of nodes = 30 Sensing range = 6m Communication range = 12m.	Coverage = 92.6%
Hongshan Kong & Bin Yu	IEEE (2019)	Enhanced Particle Swarm Optimization Algorithm	Area=20×20 m^2 Number of nodes = 10 Sensing range = 3m Communication range = 6m.	Coverage = 63.4%,
Xia-Qiang Zhao et al	IEEE (2019)	Vampire Bat Optimizer	3D Area=900×900×900ft Number of nodes = 91 Sensing radius of nodes = 170ft.	Coverage = 100%, Time = 0.1010sec
Yingying Feng et al	IEEE (2020)	Artificial Fish Swarm Algorithm	Area = 100×100 m^2 Number of nodes = 100 Sensing range = 15m Working nodes = 35.5%.	Coverage=98%
S. E. Bouzid et al	IEEE (2020)	Genetic Algorithm	Area = 300×300m^2 Number of nodes = 100 sensing radius = 60m communication radius = 100m.	Coverage = 96.7%, connectivity = 100%
K. Eledlebii et al	IEEE (2020)	Bio-Inspired Self Organizing Network (BISON)	Area = 100×100 m^2 Number of nodes = 16 Sensing radius = 16m, Communication radius = √3*16.	Coverage = 99.3%, Time = 30sec
Li Cao et al	IEEE (2021)	Chaos Social Spider Optimization Algorithm	Area = 100×100 m^2 Number of nodes = 30 Sensing range = between [5,15]	Coverage = 93.91%, connectivity = 78 %

Yin Di Yao et al	IEEE (2022)	Ant Army Search Optimization Algorithm (AASO)	Area = 500×500 m^2 Number of nodes = 5 Sensing range = 60m Communication range = 100m.	Coverage = 82.84%
H. Abdul Wasay et al	IEEE (2022)	Harris Hawk Algorithm (HHO)	Area = 20×20 m^2 Sensing radius of nodes = 6m.	Coverage = 98.289%
Jinyan Liang et al	Scientific Report (2022)	Adaptive Cauchy Variant Butterfly Optimization Algorithm	Area = 50×50 m^2 Number of nodes = 53 Sensing radius = 5m Communication radius = 10+2 or 10-2.	Coverage = 99.46 %, Running time = 21.524244 sec
Guangue Kou et al	IEEE (2023)	Sparrow Search Optimization Algorithm (SSO)	Area = 100×100 m^2 Number of nodes = 40 Sensing range = 10m Communication range = 20m.	Coverage = 98.23%
Sudeep Kumar De et al	IEEE (2023)	MOFA-GA PSO Hybrid Algorithm	Area = 225×260 m^2 Number of nodes = 25	Coverage = 100%

Above in Table 1 we can see various algorithms, strategies and method from year 2008 to year 2023 used for the coverage of wireless sensor networks (WSNs). The above Table 1 contains the input parameters of the algorithms like area in which the sensor nodes are deployed, sensing range for each sensor node means how far it can detect the target, communication range means hoe far sensor nodes can send or receive data, number of sensor nodes and also the output parameter coverage which tells us how well the area is covered. The Table 1 also shows that there are three algorithms namely, Coverage & Connectivity Preserving Routing Protocol, Distributed Coordination Algorithm and Bio Inspired Self-Organizing Network in which the coverage achieved is 99% and three algorithms namely, Harmony Search Algorithm, Vampire Bat Optimizer and MOFA-GA PSO Hybrid Algorithm in which the coverage achieved is 100%.

III. RESEARCH GAPS & CHALLENGES

Despite extensive study of WSN optimization there are some significant research gaps and challenges which are not resolved yet. This section tells the current constraints of the WSN and also gives the potential avenue to the issues.

Incomplete coverage and energy trade-off: The algorithms which are used now are either focus on the energy or the coverage of the sensor nodes, but these don not focus on the both energy and coverage effectively. So we must work on the algorithms so that they can effectively work on the energy and coverage.

Not going for the 3D: -Most of the algorithms are used for 2D in now a day there are a very few of the algorithms which are used for 3D. According to the change in world we should focus working on 3D which will be helpful for future for the pacing technology of WSN.

Node Mobility: -When the mobile WSN are deployed they move after an iteration, so it is difficult to achieve good coverage and connectivity. We must work on getting the good coverage and connectivity despite the movement of sensor nodes.

Fault tolerance: -When there is fault in a node of the WSN then all the connectivity is affected by which the coverage is also affected. We must design the network in a way that if there is fault in a sensor node then the connectivity must not be affected.

Energy Constraint: -sensor nodes have limited energy or battery life so replacing or recharging then in some areas is impractical. To overcome this problem, we must utilize the sensors more efficiency so that they can work longer with the provided battery life.

IV. CONCLUSION

The optimization of WSN remains a critical area of research. This review shows various optimization algorithms that are used in the optimization of the WSN over the years. There is significant progress made in the coverage, network lifetime, energy consumption of WSN. But there are still some gaps and challenges which we will have to overcome in the coming research of WSN. As for the future the work can be done refining these algorithms or also applying new algorithms, so that the difficulties we are facing like more of the area is covered with less number of sensor nodes, connectivity and over-coverage etc. will be solved.

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