

A Comprehensive Review of Coverage and Connectivity in 3D Wireless Sensor Networks

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Abstract— As wireless sensor networks (WSNs) rapidly move into widespread deployment in diverse three-dimensional (3D) environments from urban infrastructures to natural ecosystems, the utilizations of WSNs has increased. Such 3D settings lend themselves to unique coverage and connectivity challenges and opportunities. In this review paper, we discuss in detail various current state of the art techniques and methodologies to improve the coverage and connection in 3D WSNs. We then explore systematically a variety of approaches, including: sensor placement algorithms, network topology control, and energy efficient communication protocols. We also talk about the trades-offs and metrics that affect the design and deployment of 3D WSNs. By presenting these results, and using this review, we identify promising doors for future work that will lead towards developing more efficient and resilient 3D WSNs. The findings we report provide useful guidance for researchers and practitioners interested in the most effective ways to deploy and operate WSNs in highly three-dimensional spaces.

Index Terms—WSNs, 3D Coverage, Network Connectivity, Sensors, Topology Control, Energy Efficiency.

I. INTRODUCTION

Today, Wireless sensor networks (WSNs) are proven to be an important basic technology for plenty of applications, e.g., environmental monitoring, industrial automation and smart cities [1]. These networks consist of spatially distributed sensor nodes which observe and record the parameters of the physical or environment and wirelessly transmit this information to a central repository. Much research has been done on two dimensional (2D) WSNs, however complexities and potential application of three dimensional (3D) WSNs are becoming more relevant [2]. WSNs deployed in 3D environments offer distinct challenges and opportunities not supported by the conventional 2D methods.

Coverage and connectivity becomes much more intricate in 3D environments such as urban landscapes, underwater regions, and complex industrial environments [3]. Coverage of the sensor network is the ability to supervise a Geographical area and ensuring each point of interest is within detection range of at least one sensor. However, there is a difference between connectivity [4] and network connectivity, i.e. network's ability to maintain communication links from among the sensor nodes that facilitate the transfer of data from one location to another in an efficient manner. Achieving the best coverage and connectivity in 3D WSNs allows for the optimization of the reliability, efficiency [5], and lifespan of these networks. Several strategies have been proposed to address these challenges and include advanced sensor placement algorithms, sophisticated network topology control methods, and energy efficient communication protocols [6].

For example, Du (2020) showed how optimally deploying sensors for 3D terrains based on the DPSOVF algo. results in much better coverage and network efficiency.

This work aims at providing a systematic analysis and synthesis of previous research on coverage and connectivity in 3D WSNs ([7, 8]). In this paper, we will evaluate the proposed techniques and methodologies on the pros and cons of each. In addition, we will discuss the performance metrics employed to evaluate these techniques and point out the important research gaps that remain to be filled in furthering the field.

Wireless sensor networks technology is promising a new direction for computing and networking [9]. Sensor nodes located in a physical environment detect heterogeneously or homogeneously and send data toward a base station. Four units usually make up a sensor node: This includes Parts like the Sensing unit [10], but may have other parts such as processing, communication, power unit, a mobilizer and a location-finding system which will perform other duties. An analog-to-digital converter (ADC) and a sensor are both part of the sensing unit. For more analysis in the processing unit, this gives, sensors first transform analog signals into digital signals when events occur within their detecting range [12]. We may distinguish between 2-types of sensor-nodes: By dividing the sensor sub unit into contact and noncontact sensor nodes. For gathering precise measurements, the contact sensor nodes — thermocouples, thermistors, and resistance temperature detectors, for example — must be placed within a range that can securely contact the target. On the other hand, noncontact sensors rely on physical phenomena like the magnetoresistive and Hall effects that don't need direct physical contact with the target.

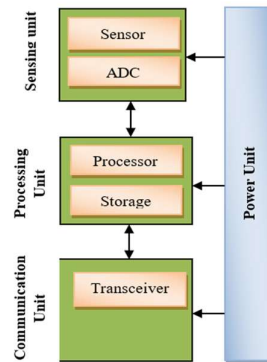


Figure 1: Architecture of Sensor-Node

A. Sensors

The second component of our system, the processing unit, consists of a processor to execute programs and a compact storage which stores the information that has been acquired [13]. The communication unit allows interaction between sensor node and network which serves to transmit and receive data from one side to another. Besides, the operational elements (sensing part) of sensor node are powered by the power unit which is the energy source. Sensor nodes are classified based on three essential criteria: specify the type of sensing, direction of sensing, the embedded sensing technology used. Several subclasses of sensors are illustrated according to each criterion. Responses to stimuli that sensors encounter can be governed by such technology, with sensor activity being converted, by changes in electrical resistance, capacitance or inductance, to an appropriate output value [14]. Moreover, the directionality of the sensor plays an important role in its operational behavior. It illustrates the fundamental differences between directional and omni-directional sensors [15]. The graphical representation helps in understanding how each type of sensor operates within a 3D wireless sensor network:

- Directional Sensors: Shown as having a cone-shaped sensing area, indicating the specific direction and limited angular range within which they operate.



Fig 2 Directional Sensor

- **Omni-Directional Sensors:** Depicted with a circular coverage area, representing their sensing ability uniformly in every direction.



Fig 3: Omni-Directional Sensor

Understanding the differences between these sensor types is crucial for designing and deploying effective 3D wireless sensor networks, as the choice of sensor significantly impacts the network's coverage, connectivity, and overall performance [16]. There is a number of sensor nodes today available in the market with light sensors, temperature sensors, pollution sensors, pressure sensors, gas sensors etc. These sensors, therefore, are widely deployed across multiple sectors including military surveillance, healthcare, industrial operations, environmental monitors, smart agriculture, intelligent buildings systems etc.[17]. Sensor networks application in each sector is supported by their own requirements and conditions to the QoS metrics which must be satisfied during sensor networks deployment.

B. Applications of Sensor Networks

The diverse spectrum of detector categories incorporated within detection networks encompasses low slice rate glamorous, seismic, thermal, visual, infrared, aural, and radar detectors. These instruments allow for detectors which can encompass differing ambient temperature parameters, moisture, vehicular movement, lightning conditions, pressure, soil composition, noise situations, presence or absence of particular object, mechanical stress situations on a connected objects and the dynamic characteristics like the speed, direction & size of an object parameters [18]. Detector bumps fulfill multifaceted places, including nonstop seeing, event discovery, event identification, position seeing, and original control of selectors. Microsensing and wireless connectivity combined into these bumps open up other kinds of operations. These operations can be totally distributed into service, environmental monitoring, healthcare, domestic, and colorful marketable disciplines [19]. Likewise, this bracket frame can be expanded to encompass fresh orders similar as space disquisition, chemical processing, and disaster relief

In Environment: The application of WSNs in environmental operations stands as a pivotal and considerably delved sphere, offering innovative results for the monitoring and operation of colorful ecological parameters. WSNs play a vital part in enabling real-time data accession and analysis, easing comprehensive environmental condition monitoring [20]. These networks are particularly precious in the assessment of air and water quality, climate change shadowing, and biodiversity monitoring. The operation of WSNs extends to perfection husbandry, where detectors contribute to optimizing resource operation, and in the field of natural disaster operation, where early discovery through detector data enhances preparedness and response strategies. The flawless integration of detector bumps into ecosystems provides experimenters with unequalled perceptivity into ecological processes [21], contributing to a deeper understanding of environmental dynamics. likewise, the effective use of WSNs supports sustainable practices by empowering informed decision- making in environmental conservation and resource operation. This exploration paper delves into the dynamic realm of environmental operations of WSNs, emphasizing their significance in advancing exploration, fostering sustainability, and addressing critical environmental challenges.

In Health: The integration of wireless detector networks (WSNs) in health operations represents a groundbreaking frontier in technological advancements with profound counteraccusations for healthcare exploration and practice [22]. WSNs play a transformative part in monitoring and enhancing health issues by furnishing real- time data accession and analysis capabilities. In healthcare settings, WSNs are employed for patient monitoring, easing the nonstop shadowing of vital signs similar as heart rate, blood pressure, and temperature [23]. These networks contribute to the development of remote patient monitoring systems, enabling healthcare professionals to ever assess patient conditions and intermediate instantly when necessary. WSNs are also necessary in the perpetration of ambient supported living technologies, supporting senior individualities and cases with habitual conditions to maintain independence while icing their safety. also, the deployment of wearable bias equipped with WSNs allows for substantiated health monitoring and facilitates preventative healthcare measures. This exploration paper delves into the expanding geography of health operations of WSNs,

exploring their part in revolutionizing healthcare delivery, perfecting patient issues, and addressing contemporary healthcare challenges.

In Military: The application of wireless detector networks (WSNs) in in-service operations represents a strategic integration of slice-edge technology to enhance situational mindfulness, intelligence gathering, and functional effectiveness. WSNs play a pivotal part in military settings by enabling real-time monitoring and data collection across different terrains and functional surroundings [24]. These networks are complete at planting detector bumps for surveillance, surveillance, and target shadowing. In military operations, WSNs contribute to the creation of effective and secure communication architectures, icing flawless connectivity between stationed units and command centers. The deployment of WSNs in border surveillance enhances border security by detecting and waking authorities to unauthorized movements. also, WSNs grease the creation of smart military bases, where detectors cover structure health, logistics, and troop movements, contributing to effective resource operation and charge planning [25]. This exploration paper explores the multifaceted service operations of WSNs, emphasizing their part in contemporizing defense strategies, perfecting decision- making processes, and accelerating the overall functional capabilities of military forces [26].

Urban Application: A further opportunity is presented by the variety of possible seeing capacities that a WSN can acquire an unknown position of information about a target area, which can be a room, a structure or out-of-doors [27]. Indeed, WSNs function as a tool for analyzing the spatial and temporal characteristics of any speck of wondrousness within civic terrain, with no limit to the number of operations. In other words, most of the operations on WSN used in the civic realm concern smart homes, smart metropolises, transportation systems and structural health monitoring, that are represented and included in other parts of this subsection [28].

In Industry: WSNs can be applied in colorful artificial operations to break numerous affiliated problems. WSNs videlicet logistics, robotics, and ministry health monitoring are illustrated with the main subcategories of artificial operations. In the rest of this subsection, we study these specific orders of operations [29].

C. Factors influencing Wireless Sensor Networks designs

Several factors, including fault tolerance; production expenses; production environment; sensor network topology; hardware limitations; energy consumption; and transmission constraints are taken into account while determining a detector network architecture [30]. None of the studies in this paper experimentally examine these factors because they do not provide a comprehensive and interrelated perspective of all the factors that are contributing to the design of the detector networks and the related detector bumps. It is important that these factors are important for setting framework for protocols or algorithms for detector networks. Additionally, these pivotal factors provide a basis for scoring the various schemes.

D. Paper Organization

The structure of this manuscript is delineated as follows: Section 2 thoroughly investigates the core principles and issues for three dimensional Wireless Sensor Networks (WSNs). In Section 3, the contemporary methods for increasing coverage in three dimensional settings are evaluated and in Section 4, the approaches to achieve connectivity are studied. Section 5 deals with the overlap/combination of coverage and connectivity methodologies, which also stress the integrative approaches that produce synergistic benefits. Finally, Section 6 identifies the open research questions and potential directions for future work, and Section 7 concludes the review with a summary of key findings and insights.

By offering a thorough examination of the current literature, this review aims to provide valuable insights for researchers and practitioners working on the design and implementation of 3D WSNs, ultimately contributing to the development of more robust, efficient, and scalable sensor networks in three-dimensional settings.

II. LITERATURE REVIEW

Recently, there have been comprehensive studies about the challenges of coverage and connectivity within three-dimensional wireless sensor networks (WSNs). As a notable example, the research by Du describes an optimal sensor deployment strategy based on the DPSOVF algorithm designed for three dimensional terrains, whereby coverage and network efficiency are combined together [1]. In the same way, Hajizadeh and his colleagues have constructed the multi objective Levy flight bee algorithm to increase node deployment in order to improve network performance in such complex environments [2]. ZainEldin et al. proposed an improved dynamic deployment technique utilizing genetic algorithms to maximize coverage, showcasing a significant advancement in adaptive deployment strategies [3]. The foundational work by Akyildiz et al. provides a broad survey of wireless sensor networks, establishing a comprehensive understanding of the fundamental principles and

challenges associated with WSNs [4]. Wang's survey on coverage problems further explores various techniques and methodologies to address the intricacies of sensor network coverage [5]. Additionally, Cao et al. examined the deployment optimization of heterogeneous directional sensor networks in security monitoring, emphasizing multi-objective approaches in 3D environments [6]. Shan, Xu, and Cheng investigated target coverage with probabilistic sensors, offering insights into the deployment of sensors with probabilistic detection capabilities, which is crucial for optimizing coverage in uncertain environments [7]. Abdollahzadeh and Navimipour reviewed various deployment strategies, highlighting the importance of strategic planning in the effective deployment of WSNs [8]. Cao et al. also explored the use of particle swarm optimizers with distributed parallelism for deployment optimization in industrial 3D WSNs, emphasizing computational efficiency and scalability [9]. In fact, coverage & connectivity in WSNs has been the subject of a comprehensive survey by Tripathi et al. [10] which analyzed research issues and challenges facing the field that still fuel innovation today. Rai and Daruwala [11] introduced a composite probabilistic sensing model for the node density optimization that significantly improves sensing reliability and network performance. Saad, Senouci, and Benyattou [12] present a realistic approach for 3D WSN deployment and paid special attention to both practical and real deployment scenarios and applicability. Zaimen et al. have recently reviewed the artificial intelligence-based deployment techniques that facilitate the WSN deployment and other WSN deployment modeling related objectives modeling, opening a door to more intelligent and autonomous network configuration [13]. Pico et al. concluded with a WSN design evaluation for environmental variable measurement showing the utilization of WSNs for environmental monitoring and the need for careful network engineering [14]. Collectively these studies contribute to advance the understanding and deployment of effective coverage & connectivity strategies in 3D WSNs.

TABLE I. LITERATURE SURVEYS

Ref	Author / Year	Objectives	Tools Used	Results	Limitations
1.	Yanzhi Du (2020)	"Method for Optimal Sensor Deployment of WSNs in 3D Terrain Based on DPSOVF Algorithm."	Distributed PSO combined with 3D virtual force	Proposed outperforms others in 3D sensor deployment considering CL.	Limited communication environment affects clustering algorithm performance.
2.	Nahid Hajizadeh (2020)	"Node deployment in WSN using the new multi-objective Levy flight bee algorithm (MOLFBA)"	Hybrid MOBA, evolutionary-algorithms(EA), & Swarm-Intelligence-algorithms(SIA), MATLAB.	MOLFBA outperforms NSGAI, IBEA, and SPEA2.	Could improve algorithm speed. Apply method to underwater WSNs.
3.	Hanaa Zain Eldin (2020)	IDDT-GA for maximizing coverage in WSN.	IDDT-GA Algorithm	"IDDT GA has better coverage rate with 9.69% and min overlapping ratio with 35.43% compared to deployment based on HSO".	IDDT-GA outperforms other techniques in coverage rates and network cost.
4.	I.F. Akyildiz, (2002).	Survey on WSN algorithms.	SMECN flooding, SPIN, SAR, LEACH, Directed diffusion.	The paper studies design constraints, explores the use of such tools to achieve the design objectives, and talks about the energy efficiency of the computational nature of the scheme.	Open research issues in WSN include power efficient transceiver design.
5.	Bang Wang (2011).	To find and fix Coverage Problems in Sensor Networks.	Optimization techniques, Localized and distributed algorithms, Greedy placement algorithms,	Paper surveys research progress on coverage problems in WSN. It discusses sensor coverage models and design issues.	Gap between research in 2D plane and practice in 3D space. Lack of straight forward extension from 2D to 3D coverage solutions.
6.	Anxing Shan, (2016).	Target Coverage in WSN with Probabilistic Sensors.	PSCA algorithm	Paper presents PSCA for target coverage.	Conventional research focuses on 0/1 coverage model, not practical sensing model.
7.	Abhishek Tripathi, (2018).	To perform a survey on Coverage and Connectivity in WSNs and find key issues and challenges.	Computational geometry approaches	N/A.	Lack of practical application in 3D.

III. PROBLEM STATEMENT

For wireless sensor networks, coverage and connectivity are crucial elements to quality of service. The problem is about target coverage in WSNs. The aim is to locate the sensor nodes that will make the least number of nodes. The minimum detection coverage set containing the least number of sensors. Recent research has been directed at coverage and connectivity problems of WSNs.

These include scheduling sensor nodes into sleep state and reducing broadcast messages. However, the problem involves choosing the best positions of the sensor node placement that is with bounded conditions, obstacles, goals and energy consumption and with coverage of all regions and at the same time, connectivity. This requires that we perform well in this direction and that as you do you do not forget all the linked problems with it.

IV. NEED OF RESEARCH

With their widespread use on applications, WSNs are becoming necessary to be deployed in 3D. Traditional 2D models do not adequately describe the complexity and specific challenges inherent to working in 3D such as cities, underwater areas and industrial sites with many interconnected levels and dimensions to explore. Providing effective coverage and reliable connectivity in these 3D settings is key for the realisation of WSNs. A sensor network has coverage so that the entire region of interest can be monitored; and connectivity so that nodes can communicate seamlessly to collect and transmit the data efficiently.

However, already existing strategies and methodologies need a thorough examination of their intricacies in 3D WSNs. Synthesizing the current state of research, evaluating the effectiveness of various approaches, identifying critical tradeoffs and highlighting research gaps, broad reviews are critical. This review proposes a foundational resource for researchers and practitioners to guide future innovations and support 3D WSN deployment and performance.

Research methodology is the structured way of solving the particular research problem objectives. Machine learning algorithms like PSO, VF (virtual force) algorithm, Genetic algorithm, MOBA (Multi-objective Bee Algorithm), Levy flight random walk, and NSGA-II are some of the algorithms used in literature work but these are not sufficient for the maximization of coverage and connectivity.

Several dual algorithms have been developed for the purpose of increasing spatial coverage within limited parameters, A main part of my dissertation is the Differential Particle Swarm Optimization combined with 3dimension virtual force algorithm.

Moreover, an Enhanced Dynamic Deployment Technique based on GA which is referred to as IDDT-GA has been developed to offer better precision, thus better coverage and connectivity, but there is need to develop a new Hybrid ML based algorithm that outperform all previous works for maximization of coverage and connectivity of wireless sensors. The objective of this study is to introduce an enhanced hybrid machine learning-based algorithmic framework within a three-dimensional context.

V. FUTURE SCOPE

This study explores coverage problems in sensor networks, focusing on their applications in surveillance, monitoring, and diagnostics. It discusses sensor coverage models, design issues, and solution approaches, addressing the limitations of the conventional coverage model. The study also presents an approximation algorithm for the minimum-detection coverage problem and evaluates the design through theoretical analysis and simulations. It then describes sensing models, categorizing the coverage available, and identifying research issues and practical deployment challenges facing wireless sensor networks.

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