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Deployment Techniques in Wireless Sensor Networks, Coverage and Connectivity: A Survey

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ABSTRACT Wireless sensor networks (WSNs) have gained wide attention from researchers in the last few years because it has a vital role in countless applications. The main function of WSN is to process extracted data and to transmit it to remote locations. A large number of sensor nodes are deployed in the monitoring area. Therefore, deploying the minimum number of nodes that maintain full coverage and connectivity is of immense importance for research. Hence, coverage and connectivity issues, besides maximizing the network lifetime, represented the main concern to be considered in this paper. The key point of this paper is to classify different coverage techniques in WSNs into three main parts: coverage based on classical deployment techniques, coverage based on meta-heuristic techniques, and coverage based on self-scheduling techniques. Moreover, multiple comparisons among these techniques are provided considering their advantages and disadvantages. Additionally, performance metrics that must be considered in WSNs and comparison among different WSNs simulators are provided. Finally, open research issues, as well as recommendations for researchers, are discussed.

INDEX TERMS Coverage, connectivity, deployment techniques, power consumption, wireless sensor network (WSN).

I. INTRODUCTION

Machine to machine communication (M2M) enables machines, physical devices, and electronic devices communicate via the internet without human intervention [1]. This type of technology called the internet of things (IoT), which allows objects to be sensed or controlled remotely [2]. Wireless sensor nodes are used in order to sense, process and transmit this data among nodes until reach to the sink. Wireless sensor networks (WSNs) are composed of group sensors with collecting information capabilities that are used for monitoring and recording the physical conditions of the environment and for transmitting the collected data to the sink as well. WSNs measure environmental conditions like temperature, sound, humidity, and wind.

In recent times, WSN has gained widespread attention and has been used for many applications [3] such as military, battlefields, traffic surveillance, security monitoring, health care, machine failure diagnoses, chemical, and biological detection, environmental monitoring, agriculture, industrial monitoring [4] and transportation. Sensor nodes have limited capabilities due to small storage, low power due to battery equipped, communication cost and limited processing capabilities. Therefore, the sensor node is susceptible to node failure due to fabrication process problems, atmospheric conditions, environmental effects, and battery power depletion. In such a case, changing the battery of the node or replacing the node will be unacceptable in hostile environments such as volcanoes, deep oceans, and earthquake, where sensor nodes are deployed randomly or drawn from aircraft. This type of node failure causes coverage hole in the network and the sensed data cannot be transmitted between nodes. Therefore sink node may not receive data in order to perform the required processing.

Various challenges in WSNs led many researchers for example localization, routing, limited storage and deployment of nodes. As shown in Fig. 1, localization [5] of unknown nodes locations include distance vector

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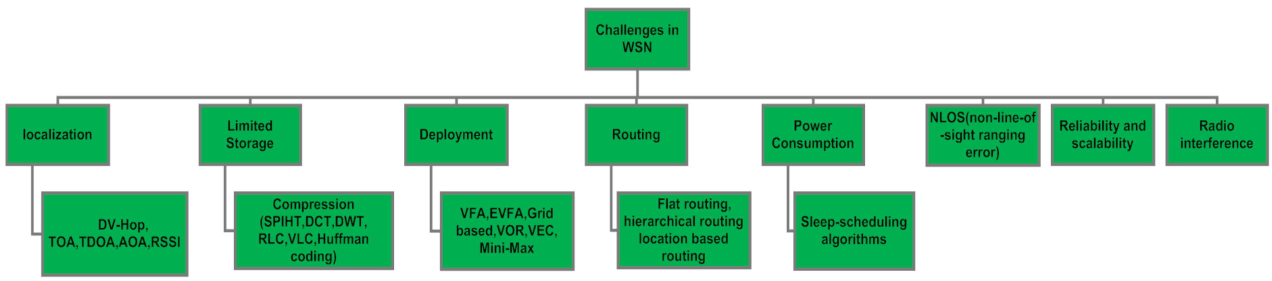

FIGURE 1. **Challenges in WSNs.**

hop (DV-Hop) [6], time of arrival (TOA) and received signal strength (RSSI). Furthermore, limited storage is a critical problem in WSN that can be resolved with data compression [7] in order to decrease transmitted data size and consequence power consumption per node will be minimized. As well, routing represents an essential factor in WSN that ensures data transmission between nodes, routing techniques can include flat routing, hierarchical routing, and location-based routing as mentioned in [8]. Finally yet importantly, power consumption, reliability, scalability, Non-Line-of-Sight (NLOS) and radio interference. Lastly, this paper focuses on an important critical problem in WSNs called, deployment of sensor nodes.

Node deployment is placing sensor nodes that fully covered the target area and ensuring connectivity to the sink node. It is considered one of the most critical problems in implementing WSNs [9], which must meet design specifications, for example, energy consumption, coverage, and connectivity. Coverage [10] is an important issue in WSN that is affected by the sensing range (r_s) of the sensor node. The target area is fully covered if every point of the area is within the sensing range of at least one sensor node and information accuracy depends upon the quality of coverage within the sensing range. Each node can detect events and objects within its sensing range and share this information with its neighbors, which is located in its communication range in order to guarantee connectivity between nodes. On the other hand, connectivity [11] is affected by communication range (R_C) of the sensor node, which ensures that every sensor node is connected to the sink directly or through a multi-hop path. The network is connected if there is one path at least between the sink node and each sensor. Coverage without full connectivity will decrease the quality of WSN because lacking connectivity there is no guarantee that the data will arrive at the sink. In addition, connectivity without coverage causes uncovered points in the target area and coverage holes will appear. Therefore, coverage and connectivity must be considered simultaneously when deploying a WSN.

The main objective of this paper is to review the recent and the main techniques for node deployment in WSN with the consideration of coverage and connectivity issues in WSN. In addition, power consumption is an important factor that must be considered. Scheduling active and sleep modes of sensor nodes after the optimal node deployment minimizes power consumption and prolong the network lifetime. The key points of this paper are:

- Classifying different coverage techniques in WSN into three main parts: coverage based on classical deployment techniques, coverage based on meta-heuristic techniques, and coverage based on self-scheduling techniques.
- Providing multiple comparisons among different coverage techniques considering their advantages and disadvantages.
- Discussing performance metrics that must be considered in WSNs and comparing different WSN simulators.

In conclusion, this paper provides some open research issues and potential future research directions that can help researchers and designers in future work. It is organized as follow; section 2 describes assumptions and preliminaries. Coverage and connectivity in WSN are discussed in section 3. Section 4 illustrates the classification of coverage techniques in WSNs. Section 5 provides simulators in WSN. In addition, Performance metrics for WSN are described in section 6. Recommendations and open research issues are discussed in section 7. Finally, section 8 concludes the paper.

II. ASSUMPTIONS AND PRELIMINARIES

Assume that for any point p located at location (x, y), there is a sensor S_i deployed at location (x_i, y_i), the Euclidean distance between sensor S_i and point p is denoted as:

$$d\,(S_i, p) = \sqrt{(x_i - x)^2 + (y_i - y)^2} \quad (1)$$

The general sensibility of S_i at any point p is defined as:

$$(Si, p) = \delta/(d(S_i, p))^k \quad (2)$$

where $d\,(S_i, p)$ is the Euclidean distance between sensor S_i and point p, and δ, k is a positive sensor dependent constants. There will be an inverse relationship between distance and sensitivity (i.e. the sensitivity of the sensor increases when the distance decreases).

A. SENSING MODELS

There are two types of sensors models that usually represent sensor coverage; the binary sensor model and the probabilistic sensor model.

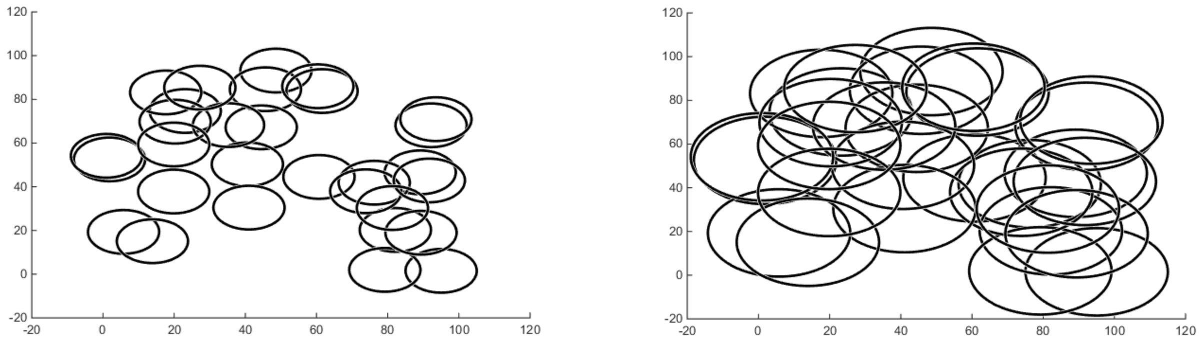

FIGURE 2. Sensing coverage of random WSN with 30 sensors. (a) The area is partially covered with $r_s = 10$. (b) The area is partially covered with $r_s = 20$.

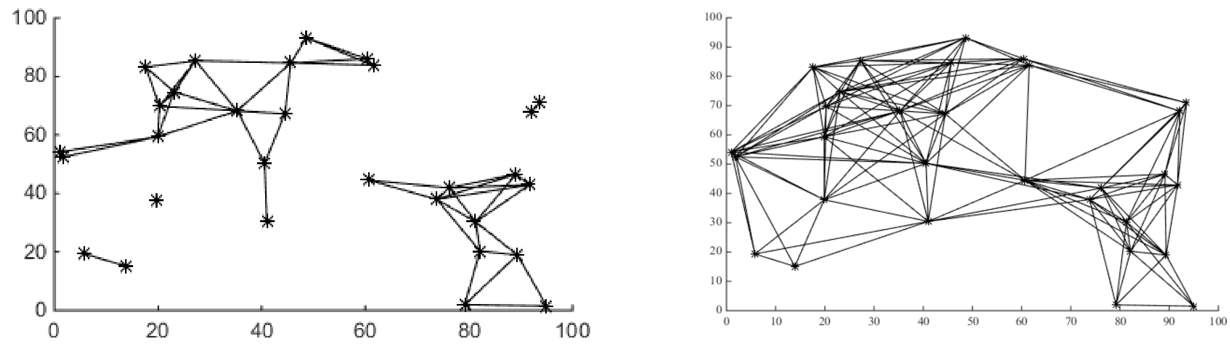

FIGURE 3. Connectivity of random WSN with 30 sensors. (a) Unconnected WSN network with $R_C = 20$. (b) Connected WSN network with $R_C = 20$.

1) BINARY DISC SENSING MODEL

The binary disk model is the simplest model as each sensor has a sensing disk with sensing range as its radius r_s. Each node is capable of detecting only points which lie within its sensing range. Equation 3 [9] shows the binary disk model which express the coverage $C_{xy}(S_i)$ of a point p by sensor S_i.

$$C_{xy}(S_i) = \begin{cases} 1 & if\ d(S_i, P) < r_s \\ 0 & otherwise \end{cases} \quad (3)$$

2) PROBABILISTIC SENSING MODEL

Since sensor detections, in reality, are inaccurate, therefore the coverage $C_{xy}(S_i)$ needs to considerable uncertainty. Coverage in probabilistic sensing model [12] is expressed in (4).

$$C_{xy}(S_i) = \begin{cases} 0, & if\ r_s + r_e \le d(S_i, P) \\ e^{-\delta a^{\beta}}, & if\ r_s - r_e < d(S_i, P) < r_s + r_e \\ 1, & if\ r_s - r_e \ge d(S_i, P) \end{cases} \quad (4)$$

where r_e is the uncertainty measure in sensor detection with value $0 < r_e\ and\ r_e < rs$, $a = d(S_i, P) - (r_s - r_e)$ and δ, β are parameters that measure detection probability in case of a target is within a distance from the sensor and at distance greater than r_e.

B. COVERAGE (SENSING RANGE (r_s))

When setting off sensors S $\{s_1, s_2, \cdots\cdots S_n\}$ are deployed in 2D area X. Each sensor is located at location (x_i, y_i) where $i = 1, 2 \ldots .n$ and each sensor has sensing range r_{s_i}. Any point P_i at an area named X is covered by sensor s_i if it is within the sensing range of s_i. Any object located within the sensing disc of a sensor is perfectly detected by the sensor. An area is k-covered if each point in the area is covered by at least k($k \ge 1$) sensor nodes. Fig. 2 (a, b) shows the sensing coverage of random WSN with 30 sensors for sensing range $r_s = 10\ m$ and $r_s = 20\ m$, respectively.

C. CONNECTIVITY (COMMUNICATION RANGE (R_C))

Nodes communication via communication range (R_C) which defines the area in which another node can be located in order to receive data. Two nodes A and B are connected, if their Euclidean distance $d(A, B) \le R_C$. Thus, the network is considered to be connected if there is at least one path between the sink node and each sensor. In addition, k-connectivity ($k \ge 1$) means that there are at least k (multiple) different paths between any two neighboring nodes in the network [10], [11]. Fig. 3(a, b) shows a network of 30 randomly deployed sensors at a square region with an area of $100{*}100\ m^2$ with communication range $R_C = 20\ m$ and $40\ m$

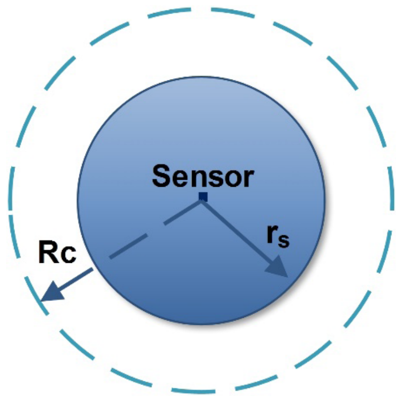

FIGURE 4. Sensing range (r_S) and Communication range (R_C).

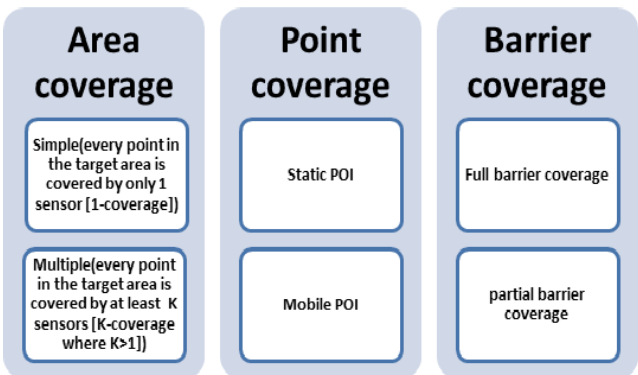

FIGURE 5. Coverage types in WSN.

respectively. Besides, Fig. 4 shows the relationship between R_C and r_s.

III. COVERAGE AND CONNECTIVITY IN WSN

Coverage and connectivity [9], [10] are an important issue in WSN. Coverage focuses on how well sensors detect behaviors in the observed area they deployed. An area is considered to be fully covered if every point of the area is within at least one sensor node sensing range (r_s). As illustrated in Fig. 5, three types of coverage are determined according to the nature of the application and the candidate's area [13].

Area coverage [9] covers the whole area according to application requirements. Either full or partial coverage is required. Full coverage is essential in applications that require a high degree of accuracies such as battlefield monitoring which requires one-full coverage or K coverage. In additions, some applications do not need full coverage and partial coverage is acceptable. Environmental monitoring applications that require only p% coverage, where $0 < p < 1$, is an example of partial area coverage. Partial coverage is an effective way to save energy of sensors and prolong the network life since the number of sensors deployed in the area is less than required for full coverage.

Point coverage is required to monitor only specific points in the area, which is called a point of interest POI. Monitoring enemy troops and bases are examples of point coverage. POI may be fixed or mobile.

Finally, monitoring events along international borders to detect illegal intrusion is an example of barrier coverage [14]. There are two barrier coverage types, full barrier coverage which means that every location of the barrier is covered by at least one sensor based on a Poisson point process model [15]. Moreover, partial barrier coverage is desirable when a number of sensors are not sufficient fully to cover the barrier.

In regard to connectivity, the network is connected if there is one path at least between each sensor node and the sink. The coverage itself without full connectivity will decrease the quality of WSN because without connectivity there is no guarantee that the transmitted data will arrive at the sink. Therefore, coverage and connectivity must be considered simultaneously when deploying any WSN. In addition, many applications do not require only full coverage but also need full connectivity in order to collect and report the required information to the sink. Besides, connectivity can also be simple if there is a single path from any sensor node to the sink known as one-connectivity or can be multiple if there are many paths between any sensor node and the sink known as K-connectivity.

Every application in WSN requires a particular degree of connectivity and coverage. Coverage is one of the measurements of WSN quality of service (QoS), and coverage without connectivity will weaken the quality of WSN because transmitted data will not able to reach the sink. There is almost a relation between r_s and R_C. The two ranges could be equal but are often different, R_C is almost larger than r_s as shown in Fig. 4.

IV. CLASSIFICATION OF COVERAGE TECHNIQUES IN WIRELESS SENSOR NETWORKS

As previously mentioned, for any point p_i at area X *is* covered by a sensor s_i if it is within the sensing range of s_i, also any point in area X is said to be K-covered if it is within the sensing range of K sensors at least. In addition to the various types of coverage presented in WSNs, diverse types of sensor nodes are deployed as well.

Homogenous sensor nodes [16] have the same power processing capabilities, sensing range, communication range, and battery power. However, heterogeneous nodes are different in at least one of those capabilities.

Nodes deployed in WSNs could be static, mobile, homogenous and/or heterogeneous [16]. Static nodes are initially deployed and keep their position fixed inside the region. They can be deployed deterministically or randomly according to environment and application requirements. The main advantages of static nodes are energy saving and reducing costs, as there is no mobility, which consumes the main energy of nodes. However, the main drawback is that there is no mobility in the network and thus, coverage holes will arise. Accordingly, mobile nodes are used to fill up the coverage holes by moving to the areas that are not covered by static nodes. Mobile nodes are deployed after the

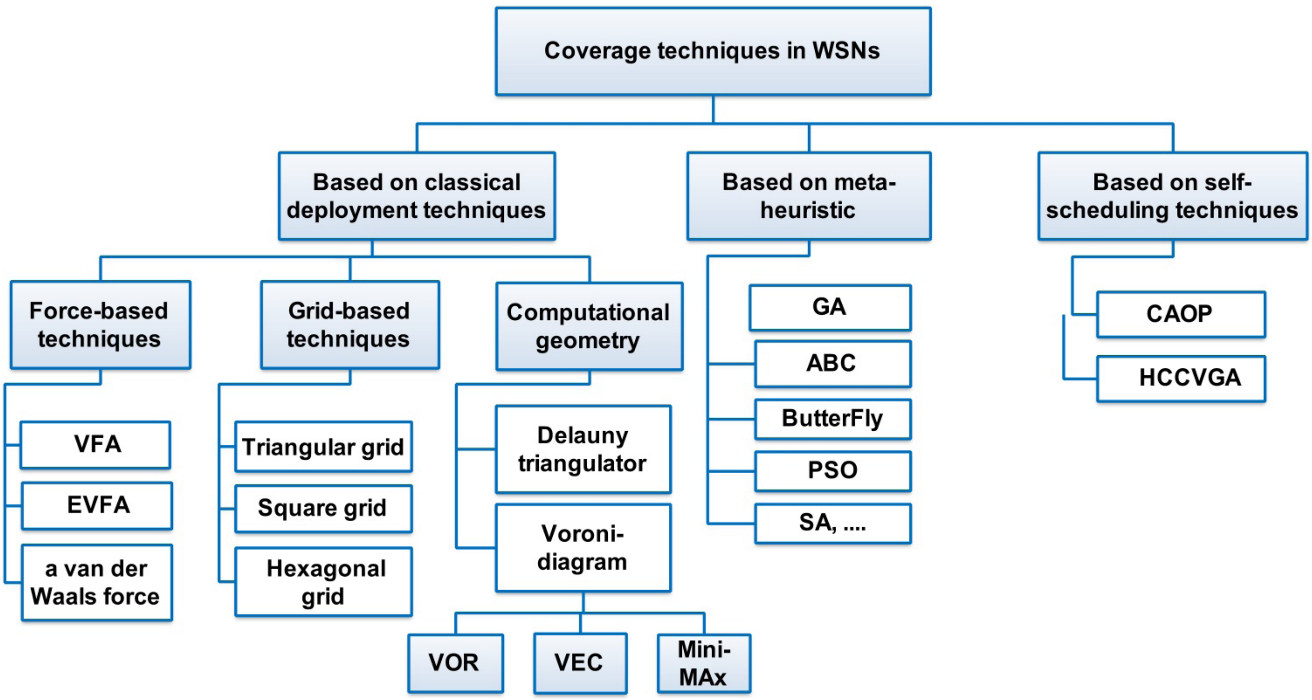

FIGURE 6. The illustrative block diagram for coverage techniques taxonomy in WSN.

initial deployment of static nodes. Then, these sensors are deployed randomly but they increase the hardware costs and consume more energy [17] due to the mobility feature. Different applications required a different degree of coverage and connectivity. Coverage and connectivity can be optimized when deploying a large number of sensor nodes. However, the main challenge in WSN is the ability to guarantee maximum coverage and connectivity using less number of sensor nodes and therefore, power consumption will be minimized [18]. However, power consumption and coverage are two contradictory objectives. Hence, bigger coverage is achieved if there is a long distance between two sensor nodes. Nevertheless, their power consumption will be higher due to the longer distance for data transmission. Whether there are mobile nodes or static nodes, coverage techniques in WSN are classified into three main parts: coverage based on classical deployment techniques, coverage based on meta-heuristic techniques and coverage based on self-scheduling techniques. Fig. 6 illustrates the classification of coverage techniques in WSN, which is discussed in the next section.

A. COVERAGE BASED ON CLASSICAL DEPLOYMENT TECHNIQUES

Depending on various applications of WSNs, the positioning of sensor nodes is very critical because the success of WSN's operation depends on the position of these nodes. Due to the random deployment of sensor node results in an irregular density, some areas are sparsely deployed while other areas are densely deployed. Thus, full coverage cannot be achieved due to the appearance of coverage holes and consequence connectivity would not be realized.

As shown in Fig. 6, classical deployment techniques are classified as force-based techniques, grid-based techniques, and computational geometry based techniques.

1) FORCE-BASED TECHNIQUES

The force-based strategy is a simple deployment strategy, which is based on virtual forces. The sensor node is subjected to attractive, repulsive or null virtual force. If the distance between two adjoining nodes is greater than a predefined threshold value, an attractive force is exerted. While, if the distance separating two neighboring nodes is less than the threshold value, a repulsive force is exerted. Otherwise, the force is null. Force-based techniques can be centralized or distributed schemes. Distrusted schemes are based on the coordinate's information of the nodes and their neighbors and all nodes have the same role and apply the same algorithm. Meanwhile, centralized approaches require a central element to perform computations and exchange messages between themselves and sensor nodes. Centralized schemes require the high computational capability for the central node, while distributed schemes consume more energy per each node that would be harmful to the network lifetime.

Virtual force algorithm (VFA) introduced in [19], enhanced initial random deployment of sensor nodes. Each sensor is subjected to three types of forces. Namely, obstacles exert a repulsive force (F_{iR}) on sensors. While, the area of preferential coverage exerts an attractive force (F_{iA}), and other sensors exert attractive or repulsive force depending on

TABLE 1. Comparison between force-based techniques.

Techniques	Advantages	Disadvantages	Force-based	Complexity
VFA [19]	- Provides acceptable coverage of the monitoring area while keeping network connectivity -Ability to deal with obstacles	-High computational capability for the sink due to new positions calculations -Low performance for heterogeneous WSN due to virtual forces exerted by static nodes. -Use mobile nodes only.	The attractive and repulsive force	High
Van der Waals force-based [21]	-Higher coverage rate. -Acceptable convergence time deal with obstacles	-Didn't consider connectivity and power consumption.	Attractive, repulsive and friction force.	High
DVFA [23]	-Achieve full coverage and connectivity. -Minimize power consumption per node.	-Additional cost in traveled distance and time compared with centralized VFA.	Attractive, repulsive and friction force.	Medium
EVFA[24]	-Deal with VFA connectivity maintenance problem and node stacking problem caused by nonplanar connectivity graph. -Provide ideal deployment of sensors nodes that ensure simple coverage and connectivity.	-Didn't deal with obstacles. -Reduces network efficiency in case of node failure because in considered only1-connectivity to the sink.	The attractive and repulsive force	Medium

the distance between nodes (F_{ij}). The Net force on sensor S_i in expressed in (5).

$$F_i = \sum_{j=1\&j\neq i}^{K} F_{ij} + F_{iR} + F_{iA} \tag{5}$$

And force F_{ij} between senor S_i and S_j is expressed in polar coordinate notation as shown in (6)

$$\underset{Fij}{\longrightarrow} = \begin{cases} \left(W_A\left(d_{ij}-D_{th}\right), \theta ij\right) & if\ d_{ij} > D_{th} \\ 0 & if\ d_{ij} = 0 \\ \left(W_R\dfrac{1}{d_{ij}}, \theta_{ij}+\pi\right) & if\ d_{ij} < D_{th} \end{cases} \tag{6}$$

where d_{ij} denotes the distance between sensors S_i and S_j, D_{th} is a defined threshold distance value, θ_{ij} is the orientation of the line segment from sensor S_i to sensor S_j, and W_A, W_R are attractive and repulsive forces measures, respectively. In addition, VFA is a centralized algorithm, during the virtual forces algorithm executed by the sink, it sends the final positions to sensor nodes, where they move directly to them. VFA provides acceptable coverage of the monitoring area while keeping network connectivity. The main drawback of VFA is that it is centralized and high computational capability for the sink due to new positions calculations. In addition, VFA performance will be degraded in heterogeneous WSN due to virtual forces exerted by static nodes [20], so mobile nodes only can be used in VFA.

Obstacles and preferential areas are modeled in [21]. They proposed a van der Waals force-based deployment algorithm for node deployment in WSN. They used Delaunay triangulation in order to define the relationship of adjacency of nodes. In order to produce acceleration for nodes to move, the friction force is added into the force equation. A new factor called pair correlation was employed to estimate the uniformity of nodes distribution. Their simulation results showed that their technique has a higher coverage rate, acceptable convergence time, and more uniformity in configuration compared to some other virtual force algorithms.

VFA for multi-robot deployment was introduced in [22]. Their research investigated the best setting for factors of the attractive force (W_A) and repulsive force (W_R). In addition, they introduced an energy-aware virtual force approach in order to maximize network lifetime and minimize power consumption among deployed robots. They used LegoTM Mind storm robots to demonstrate the effectiveness of these settings.

Distributed Virtual Forces Algorithm (DVFA) has been introduced in [23]. Randomly deployed wireless mobile sensor nodes were redeployed to ensure coverage and connectivity while minimizing power consumption per node by reducing the distance traveled by each sensor node. They performed their simulation using NS-2 and found that their proposed algorithm outperformed the centralized VFA (CVFA).

The extended virtual force-based approach was proposed in [24], and different ratios of communication range to sensing range ($R_C/r_s < 2.5$) were defined in low-R_C. They introduced an orientation force $\pi/3$ between one node and its neighbors to guarantee the continuous connectivity and drop coverage holes. Besides, in high-R_C, they proposed a rule of distance force between a node and its faraway nodes in order to prevent node stacking (i.e. where many nodes are located in the same position) from non-planar connectivity. Table 1 provides a comparison between the previously mentioned force-based techniques.

2) GRID-BASED TECHNIQUES

The grid-based strategy [25] is a type of a deterministic deployment where sensor nodes positions are fixed according to a regular grid pattern such as a triangular grid, a square grid or a hexagonal grid. According to the deployment algorithm that has been commonly used, the monitoring area is divided into small grids and sensor nodes are located in the grid center or grid vertices.

TABLE 2. Comparison between grid-based techniques.

Techniques	Advantages	Disadvantages	R_C/r_s ratio	Pattern
Optimal deployment [26]	-Provide multiple coverages and ensures network connectivity.	-Coverage rate changes with different ratios of R_C and r_s, that may degrade network performance.	$\frac{R_C}{r_s} \geq \sqrt{3}$	Triangular, square and hexagonal
optimal sensor placement [27]	-Achieve full area coverage with a minimum number of sensor nodes	-Did not consider network connectivity	$\frac{R_C}{r_s} = \sqrt{3}$	Triangular
VSGCA[29]	- Achieve coverage and connectivity with a minimum number of sensor nodes. - Minimizing power consumption. - Minimize computational complexity by using sleep scheduling	-Did not include obstacles -Did not deal with mobility	$R_C \geq 2 * r_s$	Square

The regular deployment pattern of sensor nodes in the target area can be considered a suitable solution to provide an acceptable degree of coverage and connectivity with a minimum number of nodes. Optimal deployment patterns can be obtained according to the relationship between r_s and R_C as mentioned below.

Uniform sensor deployment patterns to achieve p-coverage and q-connectivity where (q $\leq$ 6) is introduced in [26]. For different ratios between r_s and R_C, they introduced the square grid, a triangular lattice, and hexagon patterns. They compared the number of sensor nodes needed for the regular deployment patterns to achieve 1, 3, and 5-coverage and q-connectivity with $r_s = 30\ m$ using the following Equation:

$$no.\ of\ nodes = \frac{target\ area\ region}{Ta,\ Sa\ or\ Ha} \tag{7}$$

where Ta, Sa, and Ha are triangular lattice area, square grid area, and hexagon area respectively. They recommended the triangular lattice pattern as suitable deployment pattern in the case of required coverage level is ≥ 3 with ratio $R_C/r_s \geq \sqrt{3}$.

Finding the optimal deployment of sensors, in order to achieve full area coverage and long life for sensor nodes using a minimum number of nodes was discussed in [27]. They considered three deployment strategies: grid, triangular, and strip. They found that if the number of sensors is critical, then the grid deployment scheme is the best choice. However, if the number of sensors is not critical then, the strip deployment strategy represents the best case among others.

Yun *et al.* [28] also provided deployment patterns in order to achieve full coverage and K-connectivity for various relations between R_C and r_s for homogeneous WSNs. In addition, they proposed new patterns for 3- and 5-connectivity. Besides, they provided a hexagon universally elemental pattern that can generate all patterns. They additionally proved the optimal deployment patterns that achieved 6-connectivity under all ranges between R_C and r_s.

A virtual square grid-based coverage algorithm (VSGCA) of the redundant node for WSN was introduced in [29]. Their proposed algorithm has the ability to achieve an acceptable degree of coverage and connectivity with the minimum possible number of sensor nodes. Consequently, this contributed to minimizing power consumption and computational complexity by using sleep scheduling for redundant nodes. Initially, with the assumption that $R_C \geq 2 * r_s$, each sensor divides the sensing area into square grids and the nodes is redundant if all grids are covered by its neighbors. They performed their simulation on NS2 with an area of size $50 * 50\ m^2$. They concluded that their algorithm could achieve better performance in terms of lower number of nodes and shorter running time.

A grid-based deployment approach for 3D-space has been employed in [25]. They addressed random errors such as sensor placement uncertainty, which result from unexpected errors on estimated node location due to environmental conditions such as wind and rain. Besides, irregularity communication errors due to obstacles like mountains and walls were addressed in their work. They proposed a generic approach in order to find the percentage of average connectivity on 3D-grid, considering bounded and unbounded random errors. A comparison between the aforementioned different grid-based techniques as summarized in table 2.

3) COMPUTATIONAL GEOMETRY-BASED TECHNIQUES

The computational geometry strategy [30] is based on geometrical objects such as points, polygons, and line segments. Computational geometry is used to solve the art gallery famous problem (AGP) where the boundary of the entire gallery is monitored by at least one of the security guards. The AGP attempts to estimate a minimum number of cameras that can be placed in a polygonal environment in order to monitor every point in the environment. Most computational based techniques based on irregular patterns, which are more complex than regular ones.

Voronoi diagram and Delaunay triangulation [31] are the most popular computational geometry methods used in WSNs. The Voronoi diagram is a method of partitioning the area of interest into a number of Voronoi polygons based on distances between sensor nodes. Each node occupies only

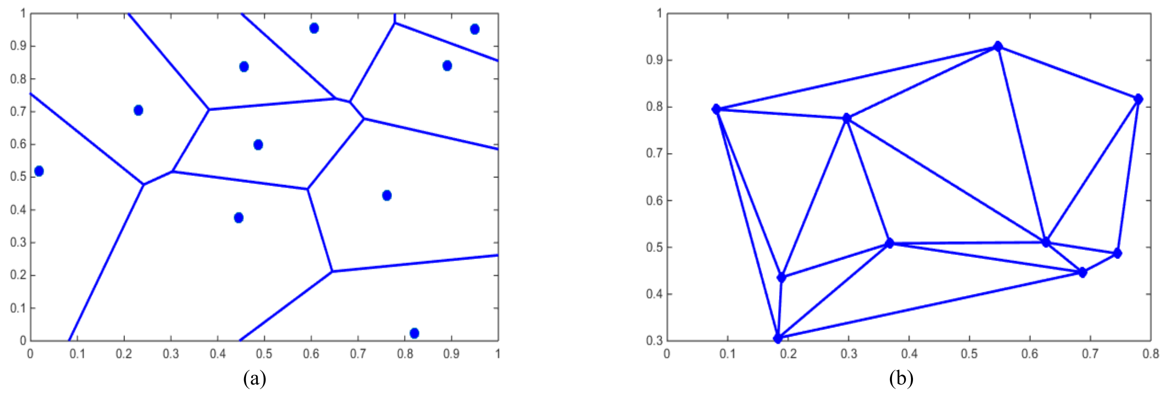

FIGURE 7. Voronoi and Delaunay triangulation diagrams. (a) Voronoi Diagram. (b) Delaunay Triangulation diagram.

one polygon, where all the inside points are closer to it than to any other sensors. Besides, Delaunay triangulation is the dual graph of the Voronoi diagram. It is constructed by connecting every two adjacent points in the Voronoi diagram whose polygons share a common edge. Mostly, Voronoi and Delaunay triangulation diagrams are used to eliminate or at least reduce coverage hole problems in WSNs. Fig. 7 shows the Voronoi diagram and Delaunay triangulation diagram.

Sung and Yang [32] introduced Voronoi diagram and distributed greedy algorithm for directional wireless sensors (sensors that have limited sensing direction and limited sensing angle). Their proposed algorithm is valid for heterogeneous sensors that have different sensing range and different sensing angles. They improved the coverage for rotatable directional sensors.

The vector-based algorithm (VEC), the Voronoi-based algorithm (VOR) and Mini-max are famous algorithms used to detect coverage hole problems. VEC is taken from the behavior of electromagnetic particles and it pushes sensor nodes away from the overcrowded covered area. Two sensors exert a repulsive force when the distance separating two nodes is small. With respect to VOR, it withdraws sensor nodes to the sparsely covered area. Finally, The Mini-max algorithm is similar to VOR as it reduces coverage holes by pushing sensor nodes closer to the furthest Voronoi vertex. Mini-max chooses the position of the target node as the point inside the Voronoi polygon that minimizes the distance to the furthest Voronoi vertex.

The main common advantage of VEC, VOR, and Mini-max is that they are Distributed algorithms that have the ability to extend to large deployment because of their ability to reduce coverage holes which ensures connectivity. Additionally, they have the ability to deal with obstacles within the monitoring area like BUG2 [33] algorithm where the sensor track the boundary of the obstacle using the right-hand rule. On the other hand, detecting coverage holes complexity and estimating new positions of the nodes are costly. In addition, they have Poor performance on initial cluster deployment and lower communication range.

B. COVERAGE BASED ON META-HEURISTIC TECHNIQUES

Several new works provide optimal trade-off among coverage, connectivity and network lifetime based on meta-heuristic techniques [34].

Two algorithms for relay node placement, which provide K-connectivity of sensor nodes, were proposed in [35]. The first algorithm is based on genetic algorithm (GA) and the second one is based on a greedy approach. They concluded that GA is better than greedy based approach as GA requires less number of relay nodes to provide K-connectivity when compared to the greedy approach. Besides, GA has higher performance because it gives global optimal solution while greedy give a locally optimal solution.

A modified genetic algorithm based relay node placement (MGA-RNP) in WSNs was presented in [36]. GA is one of the meta-heuristic approaches that considered a better solution for optimization problem when large scale WSN is considered. Their main objective was to minimize the number of relay nodes that provide maximum connectivity between the sensor nodes and relay nodes. They used a multi-objective approach and they derived fitness function according to the problem. Their experimental results describe the effectiveness of the presented algorithm.

Bendigeri and Mallapur [37] explored an energy efficient node placement algorithm (EENPA), which aims to save energy of the network while covering maximum simulation area. They use circular deployment that outperforms random deployment of nodes in terms of a network lifetime and energy consumption with few numbers of nodes.

Simulated annealing (SA) [38] is a meta-heuristic probabilistic optimization technique that simulates the annealing process in metallurgy. Annealing process by heating and cooling of a material to increase the size of its crystals and reduce their defects. A hybrid algorithm for optimal WSN deployment with a minimum number of sensor nodes was proposed in [14]. The proposed approach was built upon combining the gradient method with simulated annealing algorithm, which can solve both area and barrier coverage problems, for 1-coverage and 1-connectivity applications. Simulation results were tested on small maps $100*100$ pixels and large maps 500∗500 pixels for the two scenarios (area and barrier coverage problems). This technique was able to optimize locations of sensors and their numbers to achieve target application requirements and achieve maximum coverage.

Artificial bee colony (ABC) is a meta-heuristic search algorithm inspired by intelligent foraging behavior of honey bees in nature. It aims for finding the optimal solution to a continuous optimization problem in an iterative manner [39].

The ABC algorithm employed in [40] was applied to the dynamic deployment problem in WSNs with mobile sensors. Their proposed ABC had a great performance in increasing the coverage area of the network without considering the connectivity to the base station.

Two-particle swarm optimizers (PSO), were integrated together in [41] in order to maximize coverage and prolong network lifetime in the 3D industrial area with obstacles. The cooperative coevolutionary particle swarm optimization 2 (CCPSO2) and the comprehensive learning particle swarm optimizer (CLPSO), were employed. Increasing network coverage is achieved through deploying sensor nodes in the target area to get nodes locations, and then deploying relay nodes to increase network lifetime. Their simulation results showed that when an increasing number of relay nodes, CCPSO2 and CLPSO provide better performance by prolonging the network lifetime.

Gupta *et al.* [42] proposed a genetic approach that ensures K-coverage and m-connectivity between nodes in target-based WSNs. An efficient representation for chromosome with length equal to the number of potential positions is presented. Besides, an efficient objective function is derived. It guarantees coverage up to 3-coverage and 2-connectivity with the least number of potential positions for sensor nodes. An extensive simulation with different WSNs scenarios and a different number of potential positions is provided. This method had a superior greedy approach [43] concerning the number of selected potential positions.

Harmony search (HS)-based deployment algorithm for maximizing network coverage with minimum cost using deterministic deployment is introduced in [44]. A variable length encoding is used for each candidate solution to represent a variable number of sensor nodes in each solution. Derivation for a multi-objective function is provided. It considered coverage ratio, number of deployed nodes and the minimum distance between nodes. Experimental results proved the ability of their algorithm to achieve full coverage with a minimum number of nodes. In addition, it has fast convergence compared with a genetic algorithm. Although, it didn't consider network connectivity and nodes power consumption.

A dynamic deployment technique for optimizing coverage ratio for WSNs using whale optimization technique (MADA-WOA) is addressed in [45]. A random deployment problem with mobile sensor nodes is considered. Moreover, binary detection model is used and compared their work with maximum area detection algorithm based on electromagnetic (MADA-EM). Comparisons showed that their coverage rates are more optimal with the minimum number of sensor nodes, more stable and have fast convergence compared with MADA-EM. This technique did not consider connectivity between nodes.

Tuba *et al.* [46] Proposed coverage maximization algorithm based on firefly optimization technique which applied for mobile WSNs. The main aim is to minimize power consumption by minimization root mean of the sum squared moved distances of all sensor nodes as used in [47]. In addition, the main focus was on maximizing area coverage. Comparisons with other works of literature are provided, which achieved better coverage with less energy consumption.

Table 3 provides a comparison between previously mentioned meta-heuristic techniques.

C. COVERAGE BASED ON THE SELF-SCHEDULING TECHNIQUES

Based on the goal of minimization of power while maintaining the coverage and connectivity, an effective approach for energy saving in WSN is scheduling sleep intervals for redundant nodes, while keeping remaining nodes active to maintain network coverage and connectivity. First, each node broadcast its position and node id and listens to messages from its neighbor to obtain their positions [48]. Then, with the help of neighbor's information, it checks if its neighbors can cover its own sensing area if so it turns off itself. Finally, each node waits a random period of time and also broadcast its status (active or sleep) to other nodes to avoid blind points.

Jamali and Hatami [49] proposed coverage aware schedule for optimal placement of sensors (CAOP) algorithm that can maximize the network lifetime while maintaining complete area coverage. Initially, they compute the minimum number of nodes that can cover the whole area. Then they calculate the best locations for these nodes. After that, they partition the area into sub-regions where each area sub-region is monitored by one sensor. Finally, a local scheduling procedure schedules activation order of sensor in each sub-region.

The problem of optimal deployment with coverage and connectivity problems in WSNs was addressed in [50]. They proposed a method that schedules the sensor nodes where the only minimum number of sensor nodes will be active in order to satisfy connectivity and coverage requirement that prolong the network lifetime. In addition, they introduced a heuristic for connected coverage over VGA (HCCVGA) for the optimal problem. Their proposed heuristic technique deals with the M-Connected k-coverage problem (MCKC problem) where a certain area is covered by at least k nodes. Besides, the performance of the proposed heuristic has the same trend of network lifetime as the optimal solution.

Learning Automata for partial coverage algorithm (PCLA) introduced in [51]. They implement a sleep scheduling approach, minimizing the number of active sensor nodes in order to cover the desired region of interest and maintaining connectivity with the sink node. PCLA consisted of two phases, learning phase to select the minimum number of nodes that grantee connectivity between nodes according to

TABLE 3. Comparison between different meta-heuristic techniques.

Techniques	Advantages	Disadvantages	Meta-heuristic algorithm
A Hybrid Algorithm[14]	-Solve area and barrier coverage with a minimum number of nodes.	-Reduces network efficiency in case of node failure because in considered only1-connectivity to the sink.	gradient method, simulated annealing (SA)
GA[35]	- Requires less number of relay nodes to provide K-connectivity	- Consume more power consumption	Genetic algorithm (GA)
MGA-RNP [36]	- Minimize the number of relay nodes that provide maximum connectivity. - Implement a multi-objective fitness function that maximizes network efficiency	- High power consumption	Genetic algorithm (GA)
EENPA[37]	-Achieve area coverage with a minimum number of nodes -Minimize power consumption per node	- Didn't ensure network connectivity	---
ABC [40]	-Increase coverage for monitoring area	-Didn't ensure network connectivity -High power consumption	ABC
PSO [41]	-Maximize network coverage and prolong network lifetime. -Used heterogeneous sensor and relay nodes. -Deal with obstacles in 3D space	- Didn't ensure network connectivity	CCPSO2, CLPSO
GA [42]	- Ensure k-coverage and m-connectivity with a minimum number of sensor nodes	- Suitable for target based-WSNs not for random deployment.	Genetic algorithm (GA)
HS [44]	-Maximize area coverage with a minimum number of sensor nodes.	- Designed for deterministic deployment only - Didn't ensure network connectivity	Harmony search (HS)
MADA-WOA [45]	- Maximize area coverage with the minimum number of nodes. - Stable	- Didn't ensure network connectivity -High processing time	Whale Optimization algorithm (WOA)
Firefly [46]	- Increase area coverage -Minimize nodes' power consumption	- Increase network cost	Firefly optimization algorithm
CM-IA [47]	- Increase area coverage -Minimize redundant area between nodes	- Maximize network cost	Immune Algorithm (IA)

predefined constraints. The second phase checks if partial coverage is not met, additional sensor nodes are activated.

Table 4 summarizes deployment techniques for wireless sensor network with coverage, connectivity, and power consumption performance metrics. Besides, it surveys techniques are listed previously in this section. As illustrated from table 4, most of the works have considered coverage and connectivity problems, but few of them have considered power consumption, which considered an important issue that must be considered with coverage and connectivity. It is observed that meta-heuristic based techniques have a great performance for WSN, because of their ability to optimize multi-objective function including coverage, connectivity, and power consumption.

V. SIMULATORS FOR WSN

There are many simulators for WSN used to evaluate different network topologies without implementation in the real world. They are used by many researchers to evaluate their contributions and hypotheses. There are many simulators, and here, the main focus will be on NS-2, NS-3, MATLAB, OMNET++, NetSim, and PiccSIM.

A. NS-2 (NETWORK SIMULATOR 2)

Network simulator 2 [52] is a discrete event simulator that is used for simulation and analysis of network traffic and topology. It is a great simulation tool and used by many researchers. NS-2 is based on object-oriented (OO) programming. It is developed with two languages: C++ and object-oriented tool command language (OTCL). C++ is used for adding new modules and TCL is used for simulation purpose. In addition, NS-2 is free; it can run on different operating systems such as Linux, MAC OS X, Solaris, and Windows via software called Cygwin. However, NS-2 has limitations, for example, TCL slight difficulty to understand and write. In addition, NS-2 sometimes is more complex and time-consuming than other simulators to simulate the required job. Besides, NS-2 has poor graphical support for the user.

B. NS-3(NETWORK SIMULATOR 3)

The NS-3 project [53] was developed in 2006, and it is open source discrete-event network simulator like NS-2. However, it is considered as a replacement of NS-2, not an extension. It is developed with C++ and python. NS-3 can run on Linux systems, FreeBSD and Windows via Cygwin. NS-3 like NS-2 has no graphical Tool, but graphical results can be developed using NetAnim software.

C. MATLAB

Matrix Laboratory [54] (MATLAB) is a very powerful computing programming tool that was developed by MathWorks, MATLAB has the potential power of performing matrix operations, plotting functions and data, implementing algorithms, creating user interfaces (GUIs), and

TABLE 4. Node deployment techniques in WSNs.

Algorithm	Coverage	Connectivity	Power consumption	Strategy used	Node type
VFA [19]	True (area coverage)	True	N/A	Repulsive and attractive force based	mobile nodes
a van der Waals force-based [21]	True (area coverage)	Full connectivity	N/A	Repulsive, attractive and Friction force based	mobile nodes
VFA for multi-robot deployment [22]	True (area coverage)	Full connectivity	True (maximize network lifetime)	Repulsive and attractive force based	mobile nodes
DVFA [23]	Area coverage	True	True	Force-based	Mobile Nodes
Extended VFA [24]	True (area coverage)	Full connectivity	N/A	Repulsive and attractive force based	mobile nodes
3D-grid-based [25]	Area coverage	Multiple connectivities $K \geq 2$	N/A	Grid-based Cubic pattern (3D)	Static nodes
Regular sensor deployment patterns [26]	Multiple area coverage	Multiple connectivity (K<=6)	N/A	Grid-based (regular patterns)	Static nodes
optimal sensor placement [27]	Full area coverage	N/A	True (maximize the network lifetime)	Grid-based (triangular grid)	Static nodes
Optimal deployment Patterns [28]	Full area coverage	Multiple connectivities (K=6)	N/A	Grid-based (optimal patterns)	Static nodes
VSGCA [29]	Full area coverage	Full connectivity	Minimize power consumption	Grid-based (square pattern $R_C \geq 2 * r_s$)	Static nodes
VOR, VEC, and Mini-max [31]	True (minimize coverage holes)	True	N/A	Computational geometry based (Voronoi-diagram)	Mobile Nodes
Voronoi-based diagram[32]	Area coverage	N/A	N/A	Computational geometry based (Voronoi-diagram)	Static nodes
Simulated Annealing (SA) [14]	Full coverage (area and barrier coverage)	Full connectivity	N/A	Meta-heuristic based	Static nodes
Genetic Algorithm [35]	True (area coverage)	Multiple connectivities (k=2)	N/A	Meta-heuristic based	Static nodes
MGA-RNP [36]	True (area coverage)	Multiple connectivities (K=2)	N/A	Meta-heuristic based (multi-objective approach)	Static nodes/mobile nodes (random deployment)
EENPA [37]	True (Maximize area coverage)	N/A	True (save energy of the network)	Meta-heuristic based	Static nodes/mobile nodes
ABC[40]	Maximize area coverage	N/A	N/A	Meta-heuristic based	Mobile Nodes
PSO [41]	Maximize coverage(3D-space)	N/A	True (maximize the network lifetime)	Meta-heuristic based	Static nodes
GA [43]	Multiple area Coverage	Multiple connectivities (K=2)	N/A	Meta-heuristic based	Static nodes
HS [44]	Maximize area coverage	N/A	N/A	Meta-heuristic based	Static nodes
MADA-WOA [45]	Maximize area coverage	N/A	N/A	Meta-heuristic based	Mobile Nodes
Firefly [46]	Maximize area coverage	N/A	True (minimize moved distances of nodes)	Meta-heuristic based	Mobile Nodes
CM-IA [47]	Maximize area coverage	N/A	True (minimize moved distances of nodes)	Meta-heuristic based	Mobile Nodes
CAOP [49]	Full area coverage	N/A	True (maximize the network lifetime)	self-schedule based	Static nodes
HCCVGA [50]	Multiple area coverages	Multiple connectivities	True (maximize the network lifetime)	self-schedule based	Static nodes/mobile nodes
PCLA [51]	Partial coverage	True	True (maximize the network lifetime)	self-schedule based	Static nodes

TABLE 5. Comparison of different WSNs simulators.

Simulator	Language used	Operating system support	Free or commercial	Simulator type	GUI support
NS-2	C++,TCL	Linux, Mac OS X, Solaris, Windows(Cygwin)	Free	Discrete-event	No
NS-3	C++,Python	Linux, Mac OS X, Solaris, Windows(Cygwin)	Free	Discrete-event	No
MATLAB	Java, C	Open	Commercial	Discrete-event	YES
OMNET++	C++	Linux, Unix-like system, MAC OS, windows	Free, Commercial	Discrete-event	YES
NetSim	Java, C	Open	Commercial	Event-trace	YES
PiccSIM	NS-2, MATLAB	Open	Free	Discrete-event	YES

interfacing with programs written in other programming languages, like C, C++, C#, Java, Fortran, and Python. The most significant feature of MATLAB is its flexibility in programming, in addition, Matlab enables users to develop their own functions. MATLAB includes additional package, Simulink, which adds graphical multi-domain simulation and model-based design for dynamic and embedded systems. MATLAB has various toolboxes such as image processing, fuzzy logic, neural network, aerospace, computer vision system, control system design, statistics, optimization, communication, and many others.

D. OMNET++

Objective Modular Network Testbed in C++ (OMNET++) [55] is an object-oriented modular discrete event network simulation framework. OMNET++ has gained great popularity between researchers and has a large user community. Unlike NS-2 and NS-3, OMNET++ is not only designed for network simulation tasks but also provides frameworks and tools for writing simulation. OMNET++ can run on different operating systems including Linux, MAC OS, Unix-like system, and windows. In addition, it supports GUIs for users and provides free download for research and educational purposes.

E. NetSim

NetSim (network simulator) [56] is a discrete event simulator that provides simulation for different types of networks wired, wireless, mobile and sensor networks. NetSim comes with a user-friendly GUI. It plays an important role in stimulating and developing new application models including voice, video, email, file transfer protocol (FTP), hypertext transfer protocol (HTTP) and more.

F. PiccSIM

PiccSIM [57] stands for Platform for integrated communications and control design, simulation, implementation, and modeling. PiccSIM is a platform simulation for wireless networked control systems using MATLAB (Simulink) and NS-2. PiccSIM has the ability to design, simulate, and implement wireless control systems. It was developed by automation and systems technology department and communications and networking department at Aalto University, Finland. It provides a GUI for designing and modeling network and control systems. It requires the installation of MATLAB and NS-2 on the same machine, which runs on operating system Linux or Windows or might be running on virtual machine.

A comparison among different WSNs simulators is summarized in Table 5. Although NS-2 and NS-3 are more familiar between researchers in WSN, they lack the simplicity of graphical support for users to deal with. Therefore, MATLAB and PiccSIM circumvent the major drawbacks of NS-2 and NS-3 and are more convenient for WSN simulations.

VI. PERFORMANCE METRICS

Many performance metrics have to be considered in WSNs including but are not limited to, power consumption, scalability, and reliability, signal strength, accuracy, latency, coverage, and connectivity. A brief discussion of each metric is provided below.

A. POWER CONSUMPTION

Power consumption is an important factor that must be considered when implementing algorithms in WSNs. Minimizing power consumption per each node (by increasing the network lifetime) can be obtained by decreasing the number of exchanging messages between nodes. In addition, scheduling sleep intervals for redundant nodes, while keeping remaining nodes active to maintain network coverage and connectivity, increase the network lifetime. Besides, decreasing message size transmitted between nodes, selecting the best routing method, and reducing nodes mobility have a good influence in reducing energy in WSN. Krishnan *et al.* [58] provided a theoretical calculation of the upper bound for network lifetime using the following Equation:

$$N_{lifetime} = \frac{\sum_{i=1}^{n} c_m(i,j) * l_b(i)}{K_j} \tag{8}$$

where K_j represents K-coverage with, $j = 1, 2, 3 \ldots n$, $c_m(i, j)$ is the coverage matrix and $l_b(i)$ is the lifetime of a sensor battery.

B. SCALABILITY AND RELIABILITY

Scalability is the network ability to be extended by adding more nodes while maintaining network performance.

Reliability represents data delivery. Scalability and reliability are critical issues in WSNs due to the extremely high node numbers and relatively high node density. Scalable and reliable downward routing protocol for WSNs/IoT was introduced in [59]. They introduced opportunistic source routing (OSR), which outperforms other techniques in scalability and reliability.

C. SIGNAL STRENGTH

Signal strength is a measure of link quality. It utilizes the distance between two nodes to determine node reachability during the communication process. Received signal strength indication (RSSI) describes the strength of a wireless signal and is defined in (9) [60].

$$RSSI = -10 * n * log_{10}(d) + p \tag{9}$$

where d is the distance from the sensor in meter, n is the propagation constant or path-loss exponent and p is power in reception mode (Dbm).

D. ACCURACY, AND LATENCY

Latency is a measure of delay; it measures the time it takes for a given data to get to its destination across the network. Accuracy represents the efficiency of delivered data to the destination. Reducing delay through data transmission ensures the accuracy of the network. Latency can be calculated using (10) [61]

$$Latency = output\ interval\ (s) - input\ interval\ (s) \tag{10}$$

where the output interval is determined by the server and the input interval has been set up from the microcontroller.

E. COVERAGE AND CONNECTIVITY

As mentioned above, coverage is one of the measurements of WSNs QoS, and coverage without connectivity will reduce WSN performance because that data would not reach the sink. Coverage can be calculated through probabilistic or binary disk sensing models as illustrated in section 2.1.

VII. RECOMMENDATIONS AND OPEN RESEARCH ISSUES

According to application type, nodes deployment techniques can be categorized as in-door and out-door deployment [62]. In-door deployment techniques are concerned with limited domain areas like structures and buildings. On the other hand, out-door deployment [63] is concerned with deployment nodes in large open areas under violent and hostile environments such as volcanoes, forests and deep oceans. Hence, the area of the candidate's region is an important factor in order to determine the deployment type.

- Random deployment techniques are commonly used in large open areas such as force-based techniques.
- Deterministic deployment [64] is mostly used in small areas (in-door) such as grid-based techniques.
- Mobile sensor nodes are commonly used with random deployment techniques but it consumes more energy due to mobility.
- Static nodes with regular deployment patterns are used with deterministic deployment techniques.

Besides, the nature of the monitoring area determines the coverage type;

- If the whole area needs to be covered, area coverage is the best choice.
- If specific regions or targets need observation, point coverage is acceptable.
- If the problem is related to monitoring targets along barrier or line, so barrier coverage is sufficient.

In addition, some applications need simple connectivity (one-connectivity) with the sink, which provides a single path between the nodes and sink which in turn will be more susceptible to a path failure. While other applications require more reliable connectivity in such a case, multiple connectivity (K-connectivity) with the sink is more sufficient.

Talking about open research issues most deployment techniques deal with a 2D plane. However, new applications require sensors to be deployed in 3D. Besides coverage, connectivity and power consumption, security, reliability, and scalability are also of immense importance to be considered with deployment techniques in order to provide more accurate and scalable networks. In addition, few research papers have considered obstacles in their work, however, an area coverage needs techniques to detect obstacles and get around them, as well as ensuring coverage and connectivity. Most of these studies, if not all of them, assume that each node has information about its own position with the help of manual configuration or GPS, however, in random deployments, it would be more expensive to occupy each node with the GPS. Therefore, localization techniques need to be combined with deployment techniques in order to improve network reliability and robustness.

VIII. CONCLUSION

Coverage and connectivity are critical issues in wireless sensor networks responsible for providing continues service. Many types of coverage have previously discussed. Classification of coverage techniques based on deployment techniques, meta-heuristic techniques, and self-scheduling techniques are provided. Deployment techniques are classified based on force-based, grid-based and computational geometry based techniques which provide full coverage with simple or multiple-connectivity. Additionally, some studies help in minimizing power consumption by reducing the number of deployed nodes were also summarized in this survey. Besides, with the goal of guaranteeing full coverage and energy conservation, self-scheduling techniques were also discussed, which are based on messages exchanged between nodes in order to decide whether a given node should be active or not. Furthermore, comparisons among those techniques are provided considering their advantages and drawbacks. Moreover, a comparison between different simulators that are commonly used for WSNs is provided, and performance metrics that should be considered when evaluating the performance of the deployment technique used. Finally, some open research issues and potential future research directions were provided that can be considered by researches in future avenues.

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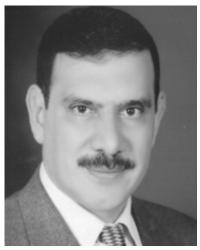

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