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► **To cite this version:**

Adda Boualem, Ayaida Marwane, Cyril de Runz. Semi-Deterministic Deployment based Area Coverage Optimization in Mobile WSN. GLOBECOM 2021 - 2021 IEEE Global Communications Conference, Dec 2021, Madrid, Spain. pp.1-6, 10.1109/GLOBECOM46510.2021.9685760 . hal-03560110

HAL Id: hal-03560110

<https://hal.science/hal-03560110>

Submitted on 18 Feb 2022

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Semi-Deterministic Deployment based Area Coverage Optimization in Mobile WSN

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Abstract—Both minimal set cover and maximum 1-coverage are known to be NP-Hard when using homogeneous and heterogeneous wireless sensor networks. The proposed solutions in the literature guaranteeing k-coverage in WSN affect either the energy, the network lifetime, or the quality of service. These solutions still incur time complexity and energy overhead that increase with WSN large-scale, connectivity and size of coverage holes. To avoid these issues, this paper proposes a minimal semi-deterministic deployment model in a mobile wireless sensor network. This model is based on Pick's theorem to guarantee a maximum 1-coverage. This requires the subdivision of the area of interest into square sub-areas according to a pre-established grid, and then an initial deployment of sensor nodes randomly around each sub-area center. The main strength of the proposed deployment approach is the minimization of the nodes' movement from their initial positions. Where, each node moves once and remains active until it is exhausted. The results show a high efficiency in terms of increasing the network lifetime and the coverage compared to some well-known approaches.

Index Terms—Mobile Wireless Sensor Network; Area Coverage; Semi Deterministic Deployment; Geometric Pick theorem.

I. INTRODUCTION

In the recent past years, Wireless Sensor Networks (WSN) have found their way into a wide variety of applications and systems with different requirements and characteristics. Consequently, it is becoming increasingly difficult to discuss typical requirements regarding hardware issues and software support. This is particularly problematic in a multidisciplinary research area such as in WSN, where close collaboration between users, application domain experts, hardware designers, and software developers is needed to implement efficient systems. Moreover, there are some other issues that are interesting to be studied, such as: deployment problems, mobility problems, homogeneity problems, communication technology problems, network topology problems, connectivity problems, coverage problems, etc.

This paper aims to propose and use a new deployment paradigm, called "minimal deployment", based on Pick's geometric theorem. The advantages behind the use of this type of the algorithm is to guarantee a fair dispersion, a perfect node connectivity with a maximum 1-coverage and a fair energy consumption. As a result, a maximum network lifetime could be reached.

The remainder of this paper is structured as follows: Section II reviews some related works about the impact of the deployment on solving coverage problems in WSN. Section III details the geometric Pick theorem, the demonstration, and its application. Section IV presents the general assumptions and details our approach and the new proposed deployment algorithm. The simulation results and analysis are introduced in Section V. Finally, the conclusion and the future works are given in Section VI.

II. RELATED WORK

A. Generalities

In the literature, deployments targeting network properties mentioned above are mainly classified into two categories: random vs. deterministic (grid-based) deployments. In random deployments, nodes can be placed either randomly to reduce the deployment cost, or based on a weighted random deployment planning, where the distributed node density is not uniform in the monitored areas. For instance, Nguyen ThiTam et al. studied in [1] the issues of relay node (RN) deployment for wireless single-hop sensor and multi-hop sensor networks in dimensional (3D) terrains. The authors proposed an efficient network lifetime maximization deployment when the RNs are directly communicating with the base station (BS). In this study, it was established that different energy consumption rates are used at different distances from the BS to ensure a uniform RN deployment, thus this type of deployment is not convenient in terms of network lifetime extension.

In [2], an Evaluated Delaunay Triangulation-based Deployment for Smart Cities is proposed, which targets not only sensor distribution, but also sink placement based on Delaunay triangulation and k-means clustering to find optimal locations to improve coverage while maintaining connectivity and robustness with obstacles existence in sensing area, but it is a deterministic strategy. In [3] Authors consider the implications of sensing and communication ranges on the network connectivity in random 3D deployments. In order to achieve a geometry as near as possible to the theoretical optimum, the work in [4] propose the Optimal evaluation algorithm to benefit from the Centroidal Voronoi Tessellation (CVT) in 2D large-scale constraining environments. This algorithm requires more criteria and tools and is difficult to be applied in 3D areas.

Reference	Network properties				Deployment		
	Cost	Connectivity	Coverage	Lifetime	Type	Technique	Targeted Space
[5]	✓	k-path	k-coverage	Node-based	Random and Geometric-based	(1)	2-D
[3]	✓	k-path	k-coverage	Network-based	Grid-based	(2)	2-D
[6]	✓	k-path	k-coverage	Network-based	Random and graph theory-based	(2)	2-D
[7]	✓	k-path	k-coverage	Network-based	Grid-based	(1)	2-D
[8]	✓	k-path	k-coverage	Uncertain Network	Grid-based	(1)	3-D
[9]	✓	k-path	k-coverage	Node-based	Node-based	(1)	2-D
[10]	✓	1-path	K-Barrier coverage	Network-based	Grid-based	(1)	2-D
[11]	✓	k-path	k-coverage	Network-based	Random	(2)	3-D
[2]	✓	k-path	k-coverage	Node-based	Geometric-based	(2)	3-D
[12]	✓	k-path	k-coverage	Network-based	Geometric-based	(2)	3-D
[13]	✓	k-path	k-coverage	Network-based	Probabilistic	(2)	3-D
[14]	✓	k-path	k-coverage	Network-based	Uncertain Model-based	(2)	3-D

TABLE I
A COMPARISON BETWEEN VARIOUS DEPLOYMENT PROPOSALS IN THE LITERATURE

Among the proposed solutions to overcome the problems of sensor deployment, Boualem et al. [15] suggested to use a new type of deployment "semi-random deployment" to minimize the disadvantages and maximize the benefits of such types of deployment. The objective behind this approach is to maintain; (a) a maximum connectivity between the sensor nodes; (b) a maximum coverage with minimal energy consumption; (c) an increase of the sensor network lifetime; and (d) a guarantee of a better quality of service (QoS).

Therefore, the deployed network connectivity is essential to ensure that sensed data are delivered correctly to the BS for processing [16].

A comparison between the different deployment strategies used for Energy-Efficient Coverage is presented TABLE I, which was inspired from [16].

Please note that in this table I: ✓ in column 2 indicates that the cost factor is considered in the corresponding reference, (1) and (2) in column 7 indicates if populating additional (redundant) nodes or mobile nodes is used in the proposal, respectively.

B. Weaknesses of different deployment strategies

This subsection summarizes the limits of the two deployment strategies (i.e. deterministic and random deployment strategies).

Among the weaknesses of deterministic deployment strategies, we can cite:

- The proposed strategies do not address how to remedy the limitation of the area of interest (AoI) coverage for deterministic deployment,
- The placement of sensors in AoI requires a preliminary study concerning; the exact nodes' positions and their orientations to allow calculating the minimum number of sensors needed.
- Knowing in which positions the sensor nodes are placed makes the network vulnerable to intrusion.

Among the weaknesses of random deployment strategies, we can notice:

- Despite the different techniques that were proposed to ensure the connectivity, some major problems of this

type of deployment remain that affect the quality of the coverage. Among these techniques, one can cite the calculation of coverage holes, the calculation of critical density, the use of surface/volume integrals, etc.

- In the literature, deployment strategies do not take into consideration the connectivity, the coverage, the lifetime, and the fault tolerance of the nodes at the same time.
- The non-accuracy of the deployment position implies a number of sensor nodes greater than the minimum optimal required number.
- A majority of the already proposed random deployment strategies were designed either to: optimize the coverage inducing energy loss or optimize the energy consumption without ensuring the optimization in the coverage of the network. All these parameters need to be considered at the same time as represented by Fig. 1.

III. PICK'S THEOREM

Let us consider a simple polygon P where i is the number of lattice points inside P , and b is the number of lattice points on the edge of the polygon as presented in [17] and [18]. Therefore, A , which is the area of the polygon is computed as (1):

$$A = i + \frac{b}{2} - 1 \quad (1)$$

where A is expressed in units of area, i represents the number of inner nodes in the polygon and b is the number of knots on its sides.

For example, on Fig. 2.(a), there is:

$$i = 41 \text{ and } b = 4$$

$$\text{Thus, } A = 41 + 2 - 1 = 42$$

A can easily be calculated by computing the area of the square in yellow (see Fig. 2.(b)) and the area of triangles 1, 2, 3 and 4.

$$A = (8 \times 8) - (1 \times 8/2) - (7 \times 2/2) - (2 \times 7/2) - (8 \times 1/2) = 64 - 4 - 7 - 7 - 4 = 42$$

The literature shows that Pick's theorem [19] is a reliable and an accurate mathematical tool. Consequently, the use of

such a tool in our algorithm will allow our model to address the problems of: the coverage, the connectivity, and the energy efficiency.

One can notice that this well-know theorem in geometry has been proved in [20] for any geometry that may be used in solving the coverage problem in wireless sensor networks.

IV. THE PROPOSED STRATEGY

A. Assumptions

To apply our coverage strategy in large areas, which consists of using minimum semi-deterministic deployment to guarantee a maximum of 1-Coverage into the AoI, we took into consideration the following assumptions:

- 1) The AoI is subdivided into $2 \times R_S$ equal diameter sub-zones. Therefore, a single sensor node can cover each sub-zone. This subdivision is intended to well cover vast areas, to achieve an equitable distribution of the nodes in the AoI in order to control the connectivity and to conserve the energy consumption in the network.
- 2) Each sensor node must be equipped with a mobile platform and a geographical position detection tool such as a GPS receiver. These devices are able to move towards a requested position.
- 3) The deployment of a large number of sensor nodes around each sub-zone (sub-area) center. This deployment is done to guarantee the longevity of the network.
- 4) Homogeneous nodes with the same characteristics are used in this study. Therefore, each neighbor node can easily compute the energy reserve of the active node (as it has the same characteristics) and control its operation against any type of intrusion.

The main intuition and objectives behind the use of Pick's theorem are:

- This theorem is used to easily recalculate the actual area covered by the sensor array. As a result, it is used as a decision support tool for redeployment or re-positioning.
- Making the deterministic deployment dynamic guarantees the expected degree of coverage using a minimum number of sensor nodes.
- Modifying the network topology according to the geographical area to be covered with a high accuracy.

B. Description of the proposed strategy

In this study, we propose the semi-deterministic deployment algorithm, denoted Semi-Deterministic Deployment Protocol (SDDP). This algorithm is centralized and is divided into 6 steps according to the conditions presented in Fig.6.

• Step 0: Pre-deployment

- The BS subdivides the area of interest into a set of N_{cl} geographical sub-areas, called "physical clusters" based on the R_S monitoring radius of the sensor node, in a way its diameter is $D = 2R_S$ (Fig. 5).
- The BS pre-configures the nodes, i.e. each node is configured using its identifier id , the transfer wait time T_{Attr} and the its cluster identifier $Idcl$,

• Step 1: Initial deployment

- The nodes are mainly deployed near the center of the area of interest to minimize the movement of the sensor nodes toward their final positions.
- The number of deployed sensor nodes is sufficient to achieve the assigned tasks.

• Step 2: Positioning

- After the initial deployment, each node moves to its corresponding geographic position and sends its to the base station to enable its tracking.
- After reaching their final positions, the nodes stay active and begin monitoring.

• Step 3: Computing the coverage degree (ρ)

- Each node must cover its sub-area (cluster) perfectly during its lifetime.
- Before the total exhaustion, each node sends an alert message to the base station to notify it about its power status.
- The other sensor nodes remain passive until an activation message is received, which contains its future geographical position.
- After receiving the data from the sensor nodes, every period, which is predefined by the base station, the latter calculates the degree of coverage ρ based on the Pick's theorem.
 - * In case this degree of coverage ρ is lower than a given threshold, thus a re-positioning procedure is triggered.
 - * In case the number of passive nodes becomes zero, then a redeployment step is triggered.

• Step 4: Re-positioning

- The base station computes the number of nodes that remain passive nd_p and the geographical area perfectly covered by Pick's Theorem, then :
 - * If the number of passive nodes nd_p is higher than the number of sub-areas $Idcl$ (i.e. $nd_p \geq Idcl$), then it sends an activation message, for a set of passive sensor nodes to allow them to move through their targeted positions.
 - * Otherwise, the BS triggers the redeployment step.

• Step 5: Redeployment

- After receiving the data from each sensor node every T_{Attr} , the BS calculates the degree of coverage ρ based on the Pick's theorem.
 - * In case this degree of coverage ρ is lower than a given threshold δ_1 (i.e. $\rho < \delta_1$), then the re-positioning process is launched.
 - * In the case where the number of passive nodes becomes lower than a given threshold δ_2 (i.e. $(nd_p < \delta_2)$), the redeployment process is launched.

C. Advantages of the proposed model

The main advantages of our model are the listed in the following points:

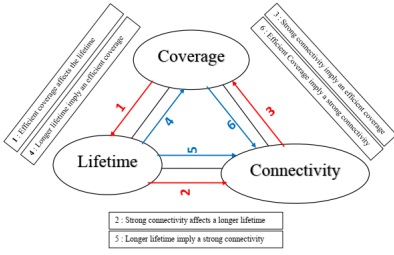


Fig. 1. The Trinomial (coverage, connectivity, lifetime) Relations.

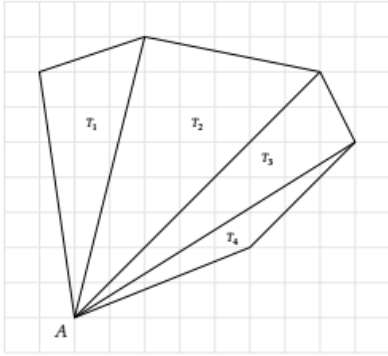


Fig. 4. A polygon P of n sides is formed by $(n - 2)$ triangles, $n > 4$.

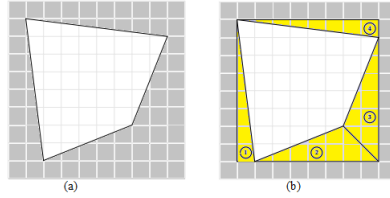


Fig. 2. (a) Polygon area calculation by the Pick's method, (b) Polygon air calculation by the classical method.

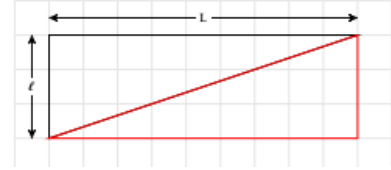


Fig. 3. right-angled triangle air calculation by the classical method.

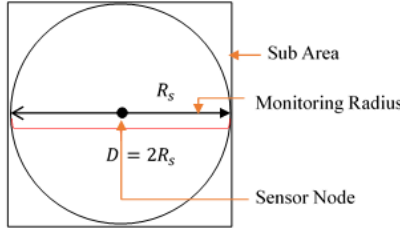


Fig. 5. The ratio of the communication and monitoring radius of a sensor node to ensure connectivity and coverage.

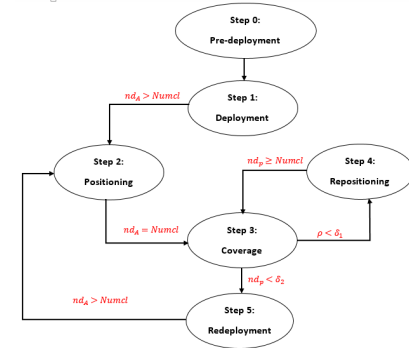


Fig. 6. Coverage strategy pipeline.

- Getting benefits from the mobility of the sensor nodes to precise geographic positions: one-time paths computed by the base station gives our model the ability to guarantee fully seamless connectivity and coverage with minimal power consumption using mobile sensor nodes.
- Using centralized algorithm: this algorithm is optimal in terms of energy consumption.
- Computing the coverage degree based on Pick's theorem: since this mathematical tool is reliable and accurate, this gives our model a better reliability and an unquestionable high accuracy.
- Studying the three main WSN problems (coverage, connectivity and energy) in one time: that is to say, if the coverage is maximized by a minimal number of sensor nodes, then a maximization at the connectivity level and a minimization at the consumption level are obtained, and vice versa.

V. SIMULATION AND EVALUATION

A. Selected deployment protocols for the comparison

We choose to compare our deployment solution with some well-known protocols, namely the strategy defined in [15], called Semi-Random Deployment Protocol (SRDP); the protocol named Flower Pollination Coverage Optimization approach (FPCOA) [21]; the Genetic Algorithm (GA) protocol [22] and the Particle Swarm Optimization (PSO) protocol [23].

Our choices have been guided by the following reasons:

- RDSPD, FPCOA, GA, PSO and SRDP are deployment-based coverage protocols as our proposed protocol SDDP.
- Genetic algorithms are currently among the most used techniques in optimization problems. The area coverage is an NP-Hard problem and the optimal approximate solution for this problem could be a suitable one.
- On one hand, FPCOA, GA and PSO use the mobile sensor nodes. On the other hand, RDSPD and SRDP protocol use static sensor nodes. Intuitively, there is a guaranteed gain in power consumption when using static approaches (RDSPD and SDRP) compared to mobile strategies (FPCOA, GA and PSO) [24], [15]. In this paper, we proposed a hybrid approach with mobile sensors that uses the random static deployment. Therefore, we have to compare to both strategies (mobile and static).
- RDSPD strategy uses a model of repeated nodes' placement in order to fully cover the AoI. This placement model is an optimal one that requires minimum number of nodes to completely cover the sensed field. Therefore, it could be seen as an optimum to be reached.
- SRDP strategy has shown its efficiency to solve the drawbacks of deterministic and random deployments [15].
- According to [21], FPCOA outperforms GA and PSO.

B. Simulation environment

For our simulation process, we took the same simulation data than the ones cited in [21]. Hence, the parameters used in this evaluation are summarized in the TABLE II.

TABLE II
COMMON DATA USED IN THE SIMULATIONS

Parameters	Value
Area of Interest (AoI)	50 m × 50 m
Communication Radius (R_c)	15 m
Sensing Radius (R_s)	15 m
Deployed Sensor Nodes Number	5 to 40 nodes
Time Units	1000 units

To apply our protocol, we divide the area of interest into L-side of sub-areas such that: $L = R_c/1.42 = 15/1.42 = 10.56m$; i.e.: 25 sub-areas.

The results of the simulations are shown in Fig. 7, Fig. 8 and Fig. 9.

C. Results analysis

In this simulation, we evaluated the coverage, the connectivity ratio, and the total energy consumption in the network for the different simulated protocols.

1) Coverage study:

The simulation results, presented in Fig. 7, show that using SDDP strategy consumes slightly more energy than SRDP strategy due to the energy consumed by the sensor nodes, when moving to the requested positions that are close to the cluster centers.

The coverage ratio of SDDP protocol reaches 100% when the number of deployed nodes increases to 40. Moreover, the coverage ratio of FPCOA reaches almost 100% if the number of nodes increases to 50 nodes, as shown in Fig. 7. This shows a real gain in terms of the minimum number of sensor nodes that needs to be deployed to achieve a perfect coverage of the area of interest.

In addition, the network keeps a perfect coverage lifetime using SDDP better than using FPCOA. This result could be explained by the fact that SDDP uses the clustering concept for the activation of a single Cluster-Head within a Cluster to act as monitoring and communication node for the captured data to the base station, which is not the case in FPCOA. Consequently, Enabling only one node at a each time by applying SDDP protocol maintains fair coverage across all sub-areas. This coverage is increased according to the number of deployed nodes in the area of interest. The coverage ratio (r) traces a linear function that has the form $r = a \times n + b$, where n represents the number of sensor nodes deployed in AoI, and a and b are two real constants. This linearity shows the efficiency of SDDP compared to FPCOA, GA, and PSO, as shown in Fig.7.

On the other hand, FPCOA protocol shows an improvement in the coverage depending on the number of deployed sensor nodes. This enhancement is not regular for each period, but it is still more efficient than the ones characterizing GA and PSO protocols. The simulation carried out in [21] illustrates better this performance shapes.

2) Connectivity study:

As depicted by Fig. 8, The connectivity ratio for SRDP and SDDP protocols remained at 100% until 400 iterations, while

the connectivity ratio for the other four protocols drastically decreased. The connectivity ratio continues to decrease as a function of time for each protocol to reach its minimum at 1000 time units. One can notice that SRDP reaches 30% and 50% for SDDP at 1000 time units, which means that the implemented SDDP strategy keeps the connectivity between sensor nodes during a long period, which explains its robustness in terms of coverage, as shown by Fig. 8.

3) Energy consumption study:

The simulation results, presented in Fig. 9, show that using SDDP strategy slightly improves the energy consumed compared to the SRDP strategy thanks to the better sensor nodes positioning on the cluster centers. Fig. 9 shows an equitable energy consumption (e) in the network when using SDDP, modeled by the function $e = c \times t + d$, where t represents the duration of the activation time of the sensor nodes deployed in AoI, and c and d are two real constants. Besides, the graph representing the energy consumption of FPCOA is a graph with fractions, which shows unfair energy consumption in the network. Fig. 9 also shows that the network is exhausted during the first 800 time units if using FPCOA. However, the network consumes only 80% of their total energy in this time when using SDDP and will consume all their total energy after 1000 time units. This result attests the effectiveness of SDDP versus FPCOA.

Consequently, Activating only one node at each time when using SDDP protocol maintains equitable energy consumption for all nodes in all sub-areas. This consumption is proved by the linear function that has the shape of $e = c \times t + d$. This linearity shows the efficiency of SDDP compared to FPCOA, GA and PSO, as shown in Fig. 9. In addition, for certain periods, FPCOA protocol energy consumption is linear. This linearity confirms its performance compared to GA and PSO, as already noted by the simulation in the work [21].

VI. CONCLUSION

This paper focuses on the 1-coverage issue on Wireless Sensor Networks (WSN). It is important to select a minimum number of activated sensor nodes in order to keep a perfect connectivity with a minimum amount of consumed energy, and, therefore to increase the network lifetime. An optimization minimal semi-deterministic deployment algorithm, denoted Semi-Deterministic Deployment Protocol (SDDP), is proposed in this paper to find the optimal nodes' locations on the AoI based on Pick's theorem to guarantee a maximum 1-coverage in a mobile wireless sensor network. It aims jointly at minimizing the total consumed energy, while guaranteeing the perfect coverage, while maintaining the connectivity during the life of the network.

The simulations show that considering the energy efficiency, the connectivity and the coverage at the same time could significantly increase the network lifetime. Consequently, it increases the connectivity and the fault-tolerance capacity of the network. It is shown by simulation that the proposed SDDP deployment protocol combined energy-efficient coverage with fault tolerance. This is why, it outperforms the previously

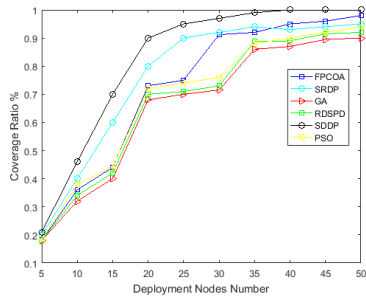


Fig. 7. Coverage ratio according to deployed number of nodes

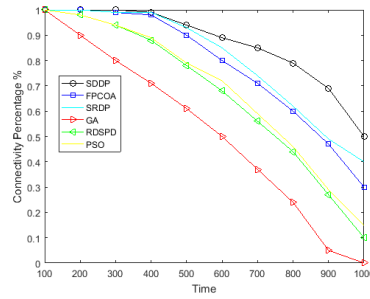


Fig. 8. Connectivity ratio according to time units

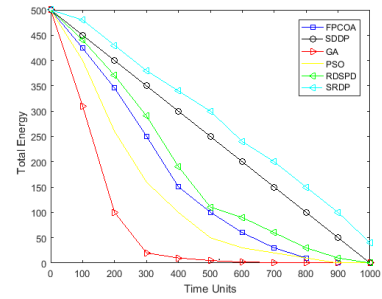


Fig. 9. Energy consumption ratio according to time units

proposed deployment strategies and it is adapted to harsh environmental conditions which cause both the node breakdowns and the link failures.

In future works, we will firstly focus on the reduction of complexity of this strategy and the energy consumption for large scale Wireless Sensor Networks, and extend our study to heterogeneous networks that involve heterogeneous sensor nodes. with their different characteristics.

ACKNOWLEDGEMENTS

This work was supported by CAMPUS France through the Project PHC Utique ADVENT (under the number CMCU Code: 20G1402 / Campus France Code: 44179PJ).

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