Evaluating the Optimal Heat Detector Deployment for Fire Detection

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Evaluating the optimal heat detector deployment for fire detection

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***Abstract*—Wireless Sensor Networks (WSNs), composed of spatially distributed autonomous sensor nodes, have a wide range of application. One of the most interesting phenomena that can be monitored by WSN, among various physical, chemical and biological phenomena and different kind of events, is fire. In case of fire presence continuous monitoring and/or recording of sensitive or restricted parts are necessary for timely response and reaction. Fire monitoring applications require accurate deployment of the sensor nodes because their positions have a dramatic impact on the effectiveness of the WSN and the efficiency of its operation. The choice of the deployment scheme depends highly on the type of sensors, application and the environment that the sensors will operate in (residential buildings, hospitals, historical buildings, malls etc.). The main advantage of WSN usage can be also identified as a simple reconfiguration and maintenance of the created infrastructure, what can be of great importance for systems that are physically unaffected by changes, but they tend to change in terms of safety (e.g. ships, oil productive platforms, etc.). Knowing that the positions of nodes have a dramatic impact on the effectiveness of the WSN and the efficiency of its operation, in this paper the various strategies for positioning nodes in WSNs are considered: grid, triangular and strip. The objective of this paper is to properly place the heat detectors in certain indoor area, in such way that next two important network design objectives are satisfied: to maximize the network lifetime after fire ignition and to use a minimum number of sensors in order to achieve full area coverage.**

Keywords- fire; heat detectors; deployment; grid; triangular; strip

I. INTRODUCTION

Security detection and surveillance based on web-based WSNs is becoming an increasingly important area of research. The advantage of the web-based WSN monitoring architecture for fire detection is that it provides a mechanism for authorized professionals to access sensed data remotely using an Internet connection (Fig. 1). In the case when a fire is detected, the fire department will be provided with a constant stream of information about the location and spread of the fire while the deployed firefighters will have information about building plan, an initial location of the fire, its spread, development of smoke, the presence of toxic gases and other factors which may affect them. To obtain these data and make them reachable to the surveillance center it is necessary to make hierarchical WSN of large numbers of scattered detectors which periodically measure the smoke concentration or temperature.

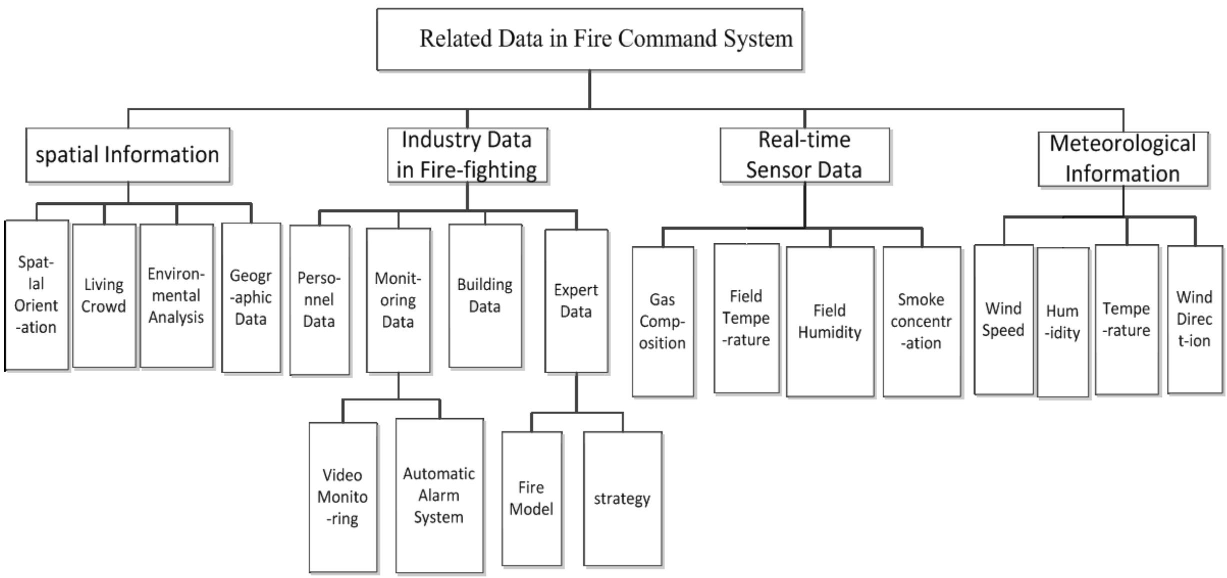

Figure 1. Fire command system and data necessary for early fire detection, prompt extinguishing and reducing damages and life losses

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The first step in forming a WSN is the deployment process [1] which can be divided into three main phases [2]:

- Pre-deployment and deployment phase;
- Post-deployment phase; and
- Redeployment of additional nodes phase.

In the pre-deployment and deployment phase, the sensor nodes are deployed in the field. Sensors can generally be deployed either deterministically (controlled) or randomly (Fig. 2).

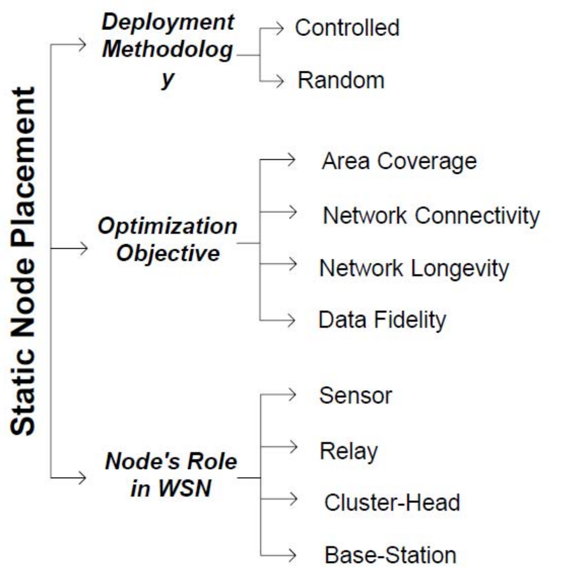

Figure 2. Different classifications of strategies for node placement in WSN

In the second phase, after deployment of the sensor nodes in the field, the network has to organize itself according to the specific task to be performed. The last of the three deployment phases mentioned above is required in order to maintain the initial node density in the field, to replace the malfunctioning or failed nodes [2].

The node's position determines the functionality, lifespan and the efficiency of the network. When designing the deployment strategies, monitoring area, sensor capability and design requirements are usually given due consideration. Thus, deployment of sensor nodes in an area should be carefully defined as it is related to the performance of WSNs such as the coverage, the connectivity and the lifetime. Controlled node deployment is viable and often necessary when sensors are expensive or when their operation is significantly affected by their position. Optimized sensor placement is not an easy problem, even in deterministic deployment scenarios. Complexity is often introduced by the quest to employ the least number of sensors in order to meet the application requirements and by the uncertainty in a sensor's ability to detect an object due to distortion that may be caused by terrain or the sensor's presence in a harsh environment [3]. In order to provide early detection of indoor fire large numbers of detectors which periodically measure smoke and gases concentration or temperature are deployed in the object. Within the fire protection and prevention, what is crucial for life saving and reduction of potential damages, neither sensor type is universally better at detecting all types of fires. Each sensor operates on a different principle and therefore may respond differently to various conditions. Heat detectors are probably the simplest and the most obvious sensors for fire detection and generally fall into two categories - fixed temperature heat detectors and rate-of-rise heat detectors. The first operates when the ambient temperature reaches a predetermined level while the second one responds when the temperature rises at a rate exceeding a predetermined value. The trigger point for both types of heat detectors should be selected in such a way that is most suitable for the situation in question.

The objective of this paper is to properly place the heat detectors such that full coverage is attained and the number of deployed sensors is minimized. The next section shows description of used deployment strategies while simulation results and comparative analysis among proposed deployment strategies are presented in Section 3. Section 4 provides concluding remarks and outlines directions for future work.

II. Sensor Deployment Strategies

Sensors used in many of the critical applications such as fire detection require their accurate deployment. In addition, many parameters need to be considered during the deployment process for efficient network operation. Using deterministic deployment strategy, the access to the monitored field must be granted and the number of required nodes for full converge could be determined. Therefore, it is suitable for optimal deployment that the coverage and/or the sensor network's lifetime are maximized. In addition, the number of the required sensors to monitor a given area in a deterministic deployment, in most cases, is more efficient [1, 4].

The ultimate objective of the practical WSN design in this paper can be defined as follows: For a specific sensing task – early and accurate heat detection, determine the number and deployment of heat detectors, so that the total network cost is minimized while the constraints of a lifetime and coverage are satisfied. Deployment strategies considered in this paper are: grid, triangular and strip.

A. Grid deployment

Heat detectors monitor a circular area A with a diameter which is the maximum distance between detectors in one direction (d), while in the other direction, this value is reduced (d_2) as the area of the square is greater than the area of the circle inscribed in it (Fig. 3). Usually it is assumed that the detector area A is adjusted to S.

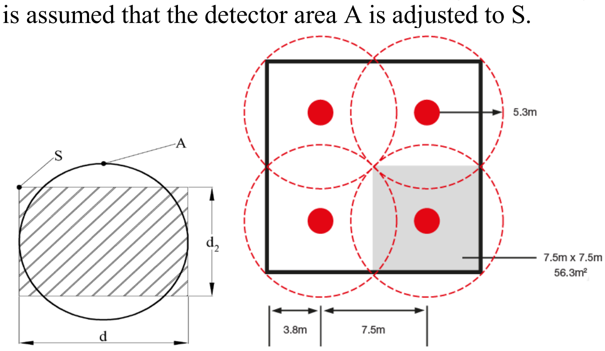

Figure 3. Area of heat detector monitoring and its positioning

The required number of detectors in an ideal rectangular room of area $P = a \cdot b$ with a flat ceiling is:

$$n = \frac{P}{S} = \frac{ab}{S} = n_R \cdot n_D \qquad (1)$$

S is the area covered by a detector ($50\,m^2$ for heat detectors). If n is not an integer, it is rounded up to the nearest whole number. Thus, n is the approximate number of detectors. Next step is to place detectors in rows that are generally parallel to the longer side of the room (Fig. 4). Number of rows (n_R) multiplied by the number of detectors in a row (n_D) should be approximately equal to or greater than n.

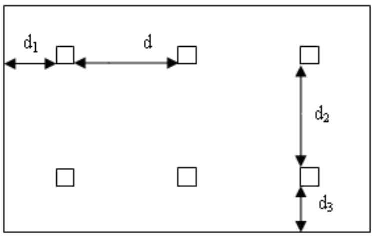

Figure 4. Detector placement in a rectangular room

The distance between the furthest rows of wall - d_3 should be approximately equal to half the distance between rows - d_2: $d_3 = 0.5 d_2$. The distance between the furthest detector in each row of wall - d_1 should be equal to half the distance between the detectors in a row - d : $d_1 = 0.5d = 0.6\sqrt{S}$ Also, the maximum distance between the detectors in one direction is: $d = 1.2\sqrt{S}$ while the distance between the detectors in the other direction is $d_2 = S/d$. All of these requirements in real life will not be fully satisfied because it will depend on the shape of the room, but they should be pursued [5].

B. *Triangular deployment*

The idea of triangular placement is to pursue a circle packing such that any three adjacent and non-collinear sensors form an equilateral triangle [6]. In this way, coverage of the targeted region can be controlled by adjusting the distance between two adjacent sensors. If the ratio between communication range and sensing range is $\sqrt{3}$, both, the connectivity and coverage requirements, are satisfied if sensors are placed at those vertices [7] (Fig. 5).

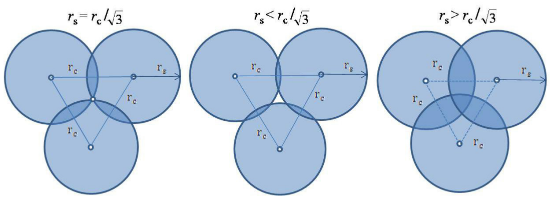

Figure 5. Sensor placement based on a triangular grid

C. *Strip deployment*

r-strip (*r* is sensing/communication range) – as being shown in Fig. 6, is a layout where sensors are placed side by side and the distance between two adjacent sensors are *r*. Assuming that the sensing and radio ranges are equal, authors of [8] first define a *r*-strip as shown in Fig. 6 (a). In a *r*-strip, nodes are placed so that neighbours of a sensor along the x-axis are located on the circumstance of the circle that defines the boundary of its sensing and communication range. Obviously, nodes on a *r*-strip are connected. The authors then tile the entire plane with *r*-strips on lines:

$$y = k\left(\frac{\sqrt{3}}{2} + 1\right) r \qquad (2)$$

such that the *r*-strips are aligned for even values of the integer *k* and shifted horizontally $r/2$ for odd values of *k*, as illustrated in Fig. 6 (b). The goal is to fill gaps in coverage with the least overlap among the *r*-disks that define the boundary of the sensing range. To establish connectivity among nodes in different *r*-strips, additional sensors are placed along the y-axis (the shaded disks in Fig. 6 (b)). For every odd value of the integer *k*, two sensors are placed at: $\left[0, k\left(\frac{\sqrt{3}}{2}+1\right) r \pm \frac{\sqrt{3}}{2} r\right]$ (3)

to establish connectivity between every pair of *r*-strips. To achieve the connectivity, an addition vertical strip is added along the y-axis in the case of infinity region and in the finite region, the strip for connectivity may not be vertical; that strip is placed in the angle such that it intersects all the horizontal *r*-strips and the intersection points need to be inside the monitored region [7] (Fig. 6 (c)).

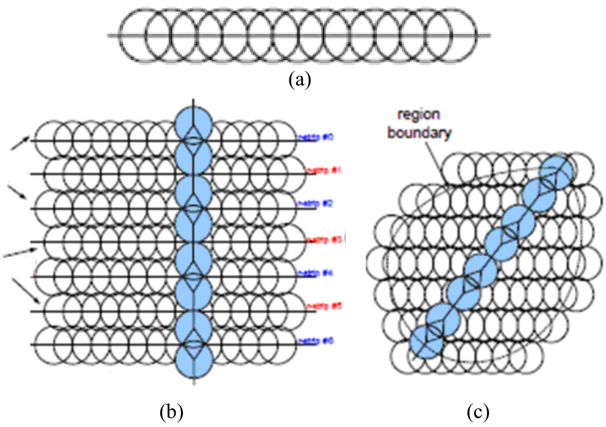

Figure 6. A r-strip: Illustration of the placement algorithm in a plane and a finite size region

III. SIMULATION RESULTS

Different heat detectors deployments above described within a specific object is performed in the rest of the paper. The room with dimensions $50m \times 19m \times 4m$, with a flat ceiling and with the average fire risk and medium fire load is observed. It is also assumed that there are no physical partitions and barriers in the monitored fields which may affect the deployment process as well as the operation of sensor networks. The aim of simulations performed using Pyrosim software tool [9] is to make a comparative analysis between proposed deployment schemes and to choose which one achieves the highest possible coverage and the longest network lifetime after fire ignition, with the least number of heat detectors. It is desirable, therefore, to find the optimal deployment, so that full coverage and long life can be achieved using minimum number of detectors. The network lifetime in this paper is defined as time until all nodes have been failed. As long as one sensor is alive, there is a possibility that information about the location and spread of the fire will be provided to a higher level. For the simulation purpose, five different positions of fire ignition and two fire source sizes are considered (Fig. 7).

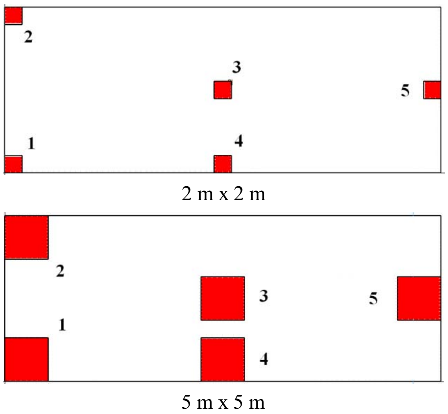

Figure 7. Fire ignition source position and size used in the simulation process

Fixed temperature heat detectors with an activation temperature of 74 ^{0}C and response time index of RTI=100 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ are used in simulations.

A. *Grid deployment*

According to grid deployment described in [5] for the observed room with known dimensions, heat detectors placement presented in next figure is achieved.

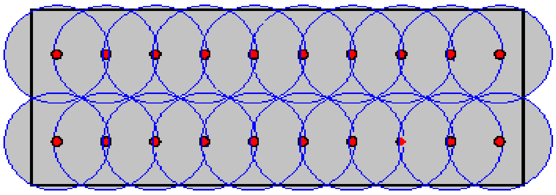

Figure 8. Heat detector grid deployment (20 detectors)

3D view of the room and heat detectors is presented in Fig. 9.

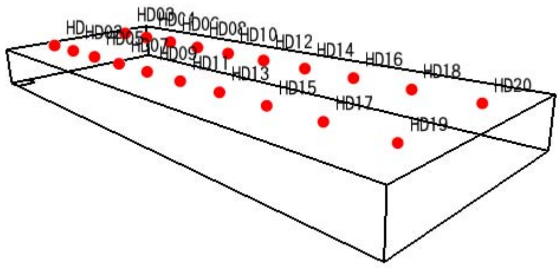

Figure 9. 3D view of heat detector deployment

Fig. 10 shows development of fire and smoke in 80th seconds from the fire ignition.

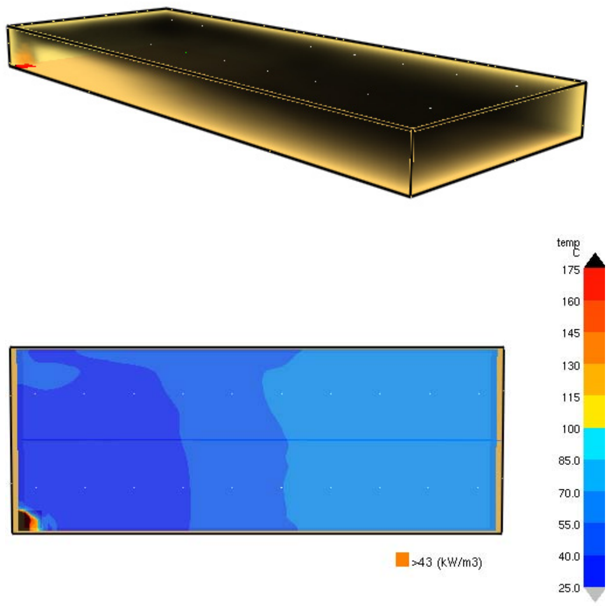

Figure 10. Development of smoke and heat in 80th seconds from the fire ignition

B. *Triangular deployment*

Heat detectors have the sensing range - r_s of 5.3 m (as it is shown in Fig. 3) and an equilateral triangle whose edge's length is $d = \sqrt{3}r_s = \sqrt{3} \cdot 5{,}3 = 9{,}1\ m$ should be formed. But in the case of the rectangular room whose dimensions are given above, full coverage in this case can't be achieved. In some cases, like for a fire position "5", fire can be located out of the detection zone. The consequences are longer detection of fire and late reaction. If sensing range is decreased from 5.3 m to 4 m, modified triangular deployment is achieved with higher number of used detectors (Fig. 11) (the minimum distance of the detector from wall of 0.5 m is satisfied). Even coverage is significantly increased still is not achieved 100% coverage.

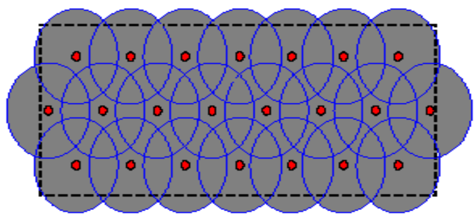

Figure 11. Heat detector triangular deployment (22 detectors)

C. *Strip deployment*

According to *r*-strip deployment strategy, presented in Fig. 6 for the given room, proposed heat detector deployment is shown in Fig. 12. Presented deployment with 20 heat detectors doesn't provide 100% coverage.

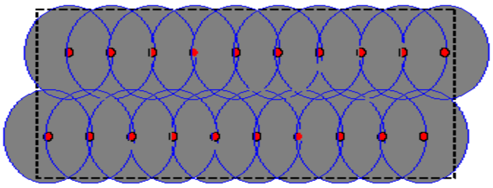

Figure 12. Heat detector strip deployment (20 detectors)

D. *Comparative analysis*

In this subchapter a comparative analysis of response times of fixed temperature heat detectors in function of fire size and its location for three considered deployment strategies is performed. For performance evaluation it will be considered:

- The shortest activation time of at least two sensors (to eliminate false alarm possibility in the case of activation of only one sensor),
- The longest activation time of last (furthest) sensor (as long as the time until last sensor failure is longer it is possible to receive data from sensor about condition in the room) and
- The minimum number of used sensors in order to achieve full coverage of monitoring area.

Fig. 13 presents obtained simulation results in the case of smaller fire source (2 m x 2 m) while Fig. 14 shows obtained simulation results for bigger fire source (5 m x 5 m).

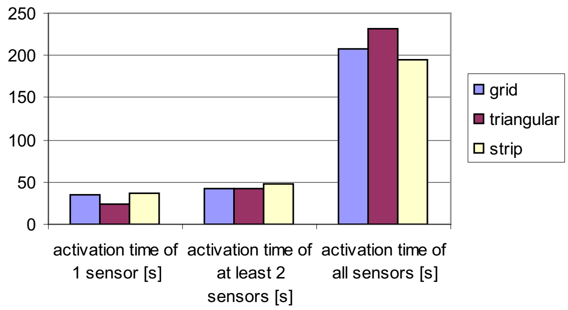

Figure 13. Average response (sensors activation times) for five proposed fire source positions and for smaller fire source size in a case of three proposed deployment strategies

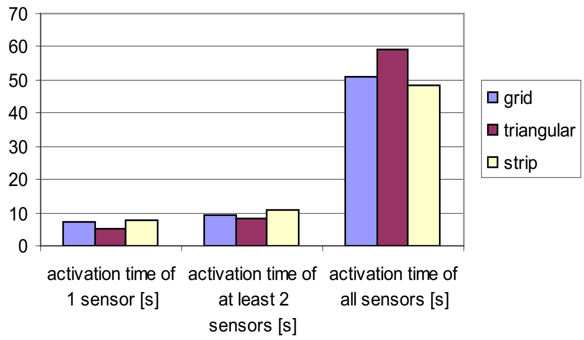

Figure 14. Average response (sensors activation times) for five proposed fire source positions and for bigger fire source size in a case of three proposed deployment strategies

From Fig. 13 it can be concluded that the triangular deployment scheme has the shortest response time of one and at least two sensors achieving the longest network lifetime at the same time.

Fig. 14 presents average values of activation times for three deployment strategy in case of bigger fire source size. Grid deployment strategy generates second best performance while strip deployment has the worst activation times and network lifetime compared to triangular and grid deployment schemes.

Comparison of Fig. 13 and Fig. 14 shows that the activation time decreases as fire size increases.

Simulation results presented in Fig. 13 and Fig. 14 shows that according to fixed temperature heat detectors activation times and achieved network lifetime, three considered deployment strategies are ranked as:

1. Triangular deployment scheme;
2. Grid deployment scheme;
3. Strip deployment scheme.

According to a number of used heat detectors and obtained coverage, considered deployment strategies are ranked as:

- Grid deployment scheme - 20 detectors, 100% coverage;
- Triangular deployment scheme - 22 detectors, slightly less than 100% coverage;
- Strip deployment scheme - 20 detectors, the less coverage compared to other two deployment strategies.

It can be concluded that the choice of deployment strategy (a first step in forming any WSN) depends on the applications, requirements and design goals. No matter what kind of object has to be monitored (e.g. residential buildings, historical buildings, hospital or ships), WSN application in fire detection requires accurate deployment of the sensors (in accordance with object's characteristics) in order to ensure fast and precise response.

IV. CONCLUSION

A performance study of predefined network design objectives in WSN when nodes are deployed under different topologies in case of fire detection considered only one of numerous possible situations. If number of sensors and achieved coverage would be crucial then the grid deployment scheme would be the best choice. The faster reaction time can be measured in tens of seconds, but in the event of a fast moving fire, these are precious seconds. Thus, if sensor price is not determining factor and very small deviations from 100% coverage can be tolerated, triangular deployment scheme in cases considered in this paper represents a compromise between obtained activation times, network lifetime, achieved coverage and number of used sensors. Nevertheless, it can be concluded that there is no single, distinctive approach to the design and deployment of sensor networks available today. There are many parameters that affect the deployment as well as the operation of WSNs. Only few of them are considered in this paper. Taking as much as it possible parameters into consideration (parameters related to the sensors, parameters related to the deployment field and parameters related to both of the sensors and the deployment field) during the deployment process should enhance the overall operation of the network as well as affecting the performance of the deployment algorithms. Directions of future work will be to take onto consideration more parameters and also to consider some other deployment algorithms, like those who involve fuzzy logic in order to find a new, optimal sensor deployment scheme. The ultimate goal will be to state the pros and cons of different deployment strategies.

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