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EVALUATING THE OPTIMAL SENSOR PLACEMENT FOR SMOKE DETECTION

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Abstract: Wireless Sensor Networks (WSNs) consist of wireless sensor nodes, where the choice of their deployment scheme depends highly on the type of sensors, their application, and the environment they will operate in. The performance of WSNs can be affected if the network is deployed under different topologies. In this paper various strategies for positioning nodes in WSNs for fire detection (grid, triangular and strip) are discussed. We propose the proper placement of the smoke sensors to satisfy two important network design objectives: to maximize the network lifetime after fire ignition, and to achieve full coverage by using a minimum number of sensors (especially in a deterministic node deployment).

Keywords: Wireless Sensor Networks, Smoke detectors, Optimal placement.

MSC: 68U20, 54A10.

1. INTRODUCTION

A Wireless Sensor Network (WSN) consists of spatially distributed autonomous sensor nodes working together for numerous sensing and monitoring services. Applications of WSN are: environmental monitoring, industrial machine monitoring, surveillance systems, military target tracking, etc. Each of the application differs in features and requirements. The application requirements vary in terms of computation, storage, and user interface. Till now, there is no single platform applicable to all applications. The development of new communication protocols, algorithms, designs, and services are needed to support diversity of applications [1].

The sensor node in the WSN is a small embedded computing device that interfaces and communicates with sensors/actuators via short-range wireless transmitters. It has limited battery resources, processing and communication capabilities. Sensor nodes form a logical network in which data packets are routed hop-by-hop towards management nodes, typically called sinks or base stations. Thus, the WSN comprises a potentially large set of nodes that may be distributed over a wide geographical area, indoor or outdoor placed. Sensed data can be stored on the Internet through web-based technologies. Users can access data remotely as long as they have an Internet connection. Today, many WSN applications use smartphones as a gateway between the sensor network or user and the Internet. This allows the sensor network and/or the users to be mobile. Implementation of a web-based WSN architecture provides a scalable solution with applicability in many areas [2]. But the design of WSN platform must deal with challenges in energy efficiency, costs, and application requirements.

One of the most interesting phenomena that can be monitored by WSN is fire. In order to provide early detection of residential fire, a large number of detectors should be deployed in buildings [3]. This is crucial for early extinguishing, life saving and reduction of potential damages. Detectors should measure periodically smoke concentration or temperature. Security detection and surveillance based on web based WSN is becoming an increasingly important area of research. The advantage of the web-based WSN monitoring architecture for fire detection is accessibility of sensed data using an Internet connection. In case when 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 the building's plan, an initial location of the fire, fire spreading, presence of toxic gases and other factors that may affect them [4].

Within the fire protection and prevention technical field, there is no such a sensor which is universally applicable in detecting all types of fires. Each sensor operates based on different principles, and therefore may respond differently to various conditions. The easiest way to detect fire at residential places is with smoke sensors, which are usually sensitive to ionization or obscuration. When choosing an appropriate smoke detector, it is important to understand and identify the characteristics of a potential fire, the environment in which the detector will be sited and the risk of fire (e.g., ION detectors are advantageous for flaming fire detection; photo detectors are beneficial for non-flaming fire detection while combining CO and ION can more accurately detect fire [5]).

In the event of a smoldering fire, a photoelectric smoke alarm clearly outperforms the ionization type. Ionization smoke alarms outperform photoelectric alarms in fast moving fire (Figure 1). In case of faster reaction, time can be measured in tens of seconds, but in the event of a fast moving fire, these are precious seconds. Photoelectric smoke alarms typically cost about twice as much as the ionization type alarms. Because of that, ionization type alarms are mostly used in fire protection.

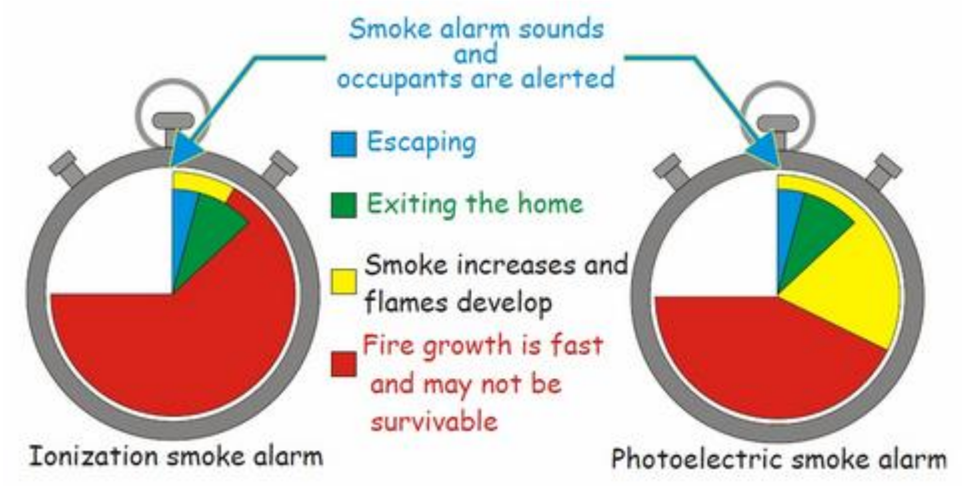


Figure 1: Ionization vs. Photoelectric smoke alarms

The first step in forming the WSN is the deployment process [6]. Sensors can generally be placed in the area of interest either deterministically or randomly [7]. The choice of the deployment scheme depends highly on the type of sensors, application, and the environment in which sensors will operate. In other words, the node's position determines the functionality, lifespan, and the efficiency of the network. Controlled node deployment is viable and often necessary when sensors are expensive, or when their operation is significantly affected by their position. The node positions have enormous impact on the effectiveness of the WSN and the efficiency of its operation. Optimized sensor placement is problematic, 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 [7].

In this paper the WSN configuration of fire detection applications is presented. One of the design optimization strategies used in the paper is to place the sensor nodes deterministically in order to meet the desired performance goals – early, accurate residential fire detection for prompt extinguishing, and reduction of damages and life losses. Knowing that the performance of WSNs can be affected when the network is deployed under different topologies, we considered various strategies for positioning nodes in WSNs: grid, triangular and strip.

The goal of this work is to properly place the smoke sensors to attain full coverage deployed sensors. Thus, simulations will be performed to satisfy two important network design objectives:

- to maximize the network lifetime in the presence of fire to provide a constant stream of information about the location and spread of the fire and the development of smoke (the network lifetime is defined as time until all nodes failed),
- to use a minimum number of sensors to achieve full area coverage as another

clear objective, especially in a deterministic node deployment.

A performance study of these network design objectives in WSNs when nodes are deployed under different topologies in case of fire detection is presented, too. Section 2 presents a literature review, while sensor placement schemes used in simulation process are presented in Section 3. Simulation results are given in Section 4, and Section 5 brings the comparative analysis of the proposed deployment strategies. Finally, Section 6 concludes the paper and points the way forward for a future work.

2. LITERATURE REVIEW

Topology issues have got more and more attention in WSN, thus the choice of the deployment strategy is crucial in most mission critical application areas. Figure 2 summarizes different categories of node placement strategies.

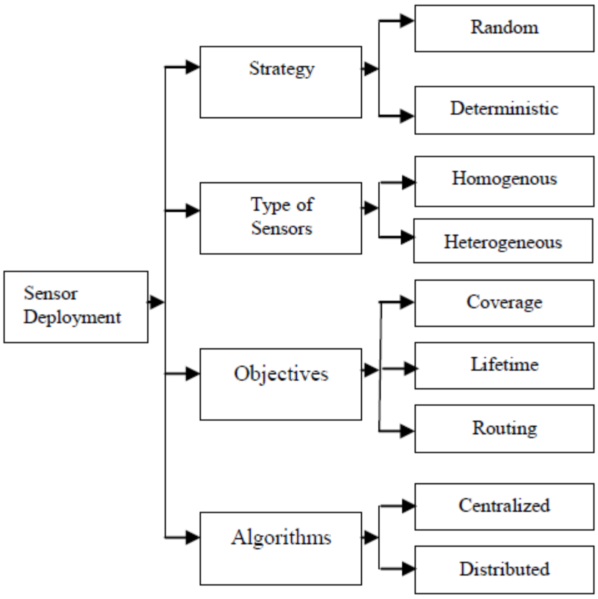


Figure 2: Different classifications of strategies for node placement in WSN [6]

Controlled sensor node placement is often pursued for only a selected subset of the employed nodes with the goal to structure the network topology and to achieve the desired application requirements. In addition to coverage, the nodes' positions affect numerous network performance metrics, such as energy consumption, delay, and throughput [7]. For example, large distances between nodes weaken the communication links, lower the throughput, and increase energy consumption.

The main focus of research in this field, as the literature show, is to find optimal sensor placement. It was found that the most prominent sensor network deployments and identified selected underlying problems were detected in system design during installation and deployments [8]. A special focus was made towards problems arising with sensor network applications and deployments in a real environment. The authors presented a number of techniques, predominantly those to be applied at run-time of a sensor network. One of the possibilities was a multi-objective particle swarm optimization - PSO and fuzzy based optimization model for sensor node deployment [9]. The objectives considered in this paper include maximizing network coverage, connectivity and network lifetime. A node deployment strategy in WSN to enhance network lifetime was proposed in [10]. The merit of the strategy lies in the fact that the nodes are deployed at pre-determined places within the network in such a manner that more nodes are placed towards the sink with the target to combat the problem of shortening of network lifetime, arising out of the fast depletion of energy of the nodes towards the sink. To resist the shortening of network lifetime further, certain locations within a layer are identified as prioritized, based on the importance of the locations in terms of sharing the workload of neighbouring locations. Various deployment models for increasing network lifetime have been discussed in [11]. Also, various system models and deployment strategies for minimum number of sensor nodes to be used and the network lifetime to be increased are discussed. DiMo, a distributed algorithm for node and topology monitoring, designed to be used with event-triggered WSN, was proposed in [12]. A novel strategy for determining an optimal sensor placement scheme in environmental monitoring, using WSN accomplished by minimizing the variance of spatial analysis based on randomly chosen points representing the sensor locations is presented in [13]. Work [14] presents the evaluation of the critical number of nodes required for target detection in a sensor network. The authors used physical characteristics of sensors and target them to derive an equation for effective sensor radius. They estimated the critical density for coverage in sensor network by using the effective radius. The authors considered variation of density with different sensor and target parameters, and extended their results to cooperative detection with different signal decay factor. Main contribution of their work is the incorporation of physical characteristics of the sensor and the target when evaluating the sensing capacity of sensor networks. Such modelling enables sensor network design where the user can decide on the density of nodes to be used, depending upon the target characteristics. The authors of [15] extended the definition of topology control to include topology construction and topology maintenance. They introduced the taxonomy for topology maintenance which frames some existing and new topology maintenance strategies and techniques (static, dynamic or hybrid, with local or global scope).

In summary, due to the diversity of applications, requirements, and design goals, there is no single, distinctive approach to the design and deployment of sensor networks available today.

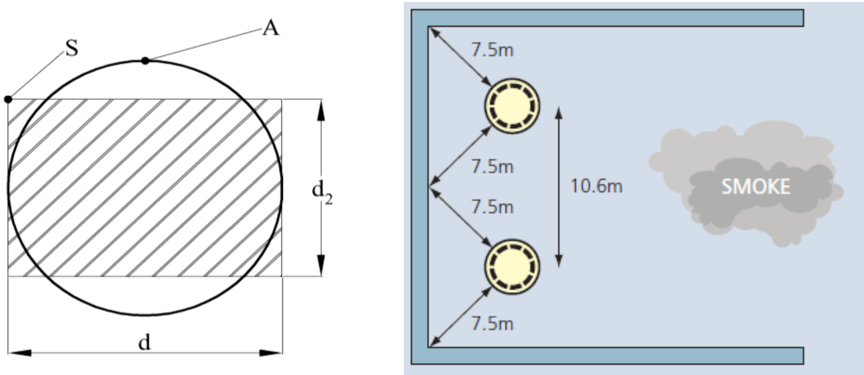
3. SENSOR PLACEMENT STRATEGIES

Sensors used in many critical applications, such as fire detection, require accurate deployment. In addition, many parameters need to be considered during the deployment process for efficient network operation. Therefore, the ultimate objective of the practical WSN design is related to early and accurate smoke detection, which will determine the number and placement of smoke sensors, so that the total network cost is minimized, while the constraints of a lifetime and coverage are satisfied.

When designing the deployment strategies, monitoring area, and sensor capability (sensing range and transmission range), design requirements (area coverage and lifetime) are usually given. Thus, deployment of sensor nodes in the area should be carefully defined as it is related to the performance of WSNs, such as the coverage, the connectivity and the lifetime. Deployment strategies considered in this paper are: grid, triangular, and strip.

3.1. Grid placement

Smoke detectors monitor a circular area A with a diameter presenting the maximum distance between detectors in one direction (d), while in the other direction, the value is reduced (d_2) as the area of the square is greater than the area of the circle, as presented in Figure 3 (a).



(a) area of smoke detector monitoring (b) smoke sensor positioning

Figure 3: Area of smoke detector monitoring and its positioning

It is assumed that the detector area A is adjusted to S ($A = S$).

According to Figure 4:

- the maximum distance between the detectors in one direction is:

$$d = 1.2\sqrt{S} \tag{1}$$

- the distance between the detector and the wall in one direction:

$$d_1 = 0.5d = 0.6\sqrt{S} \tag{2}$$

- the distance between the detectors in the other direction:

$$d_2 = \frac{S}{d} \tag{3}$$

- the distance between the detector and the wall in the other direction:

$$d_3 = 0.5d_2 \tag{4}$$

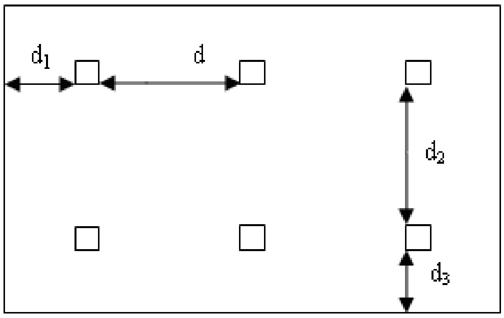


Figure 4: Detector placement in a rectangular room

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

$$n = \frac{P}{S} \tag{5}$$

S, the area covered by a detector ($100\ m^2$ for smoke detectors and $50\ m^2$ for heat detectors). If n is not an integer, it is rounded up to the nearest whole number, n is an approximate number of the detectors.

Next step is to place detectors in rows that are generally parallel to the longer side of the room. These requirements in real life cannot be fully satisfied because they depend on the shape of the room. For square room, number of rows (n_R) multiplied by the number of detectors in a row (n_D) could be calculated according to Eq. (6) [16]:

$$n = \frac{P}{S} = \frac{ab}{S} = n_R \cdot n_D \tag{6}$$

In other words, the results of the previous equation should be approximately equal to or greater than n.

In a case study, testing the arrangement can be done by checking the distance from the farthest point in the room to the nearest detector. Usually, this will be the distance of the point that is the projection of the intersection of rectangle diagonals, whose tops are the detectors on the highest distance, and/or horizontal distance from the corner of the room to the nearest detector (Figure 3 (b)). If these distances, from the most distant point to the projection of the nearest detector, are less than the maximum distances (7.5 m), the proposed arrangement is acceptable. Otherwise, there is need to increase the number of detectors and the density of coverage.

3.2. Triangular placement

Three sensors having the sensing range of r could cover the maximum continuous area if they are located at the vertices of an equilateral triangle whose edge's length is:

$$d = \sqrt{3} \cdot r \tag{7}$$

The idea, as depicted in Figure 5, is to pursue a circle packing similar to any three adjacent and non-collinear sensors [17] which form an equilateral triangle. In this way, coverage of the targeted region can be controlled by adjusting the distance d between two adjacent sensors. If the ratio between communication range and sensing range is $\sqrt{3}$, both the connectivity and the coverage requirements are satisfied if sensors are placed at those vertices [18].

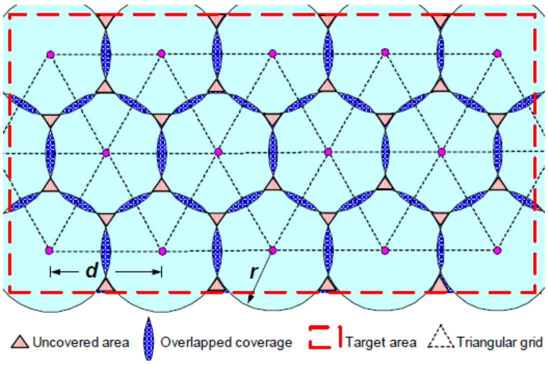


Figure 5: Sensor placement based on a triangular grid. Coverage can be controlled by adjusting the inter-node distance “d”.

3.3. Strip placement

A r-strip (r is sensing/communication range), as shown in Figure 6, is a layout where sensors are placed side by side. The distance between two adjacent sensors is r. Assuming that the sensing and radio ranges are equal, a r-strip is first defined (Figure 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 [19]. Obviously, nodes on a r-strip are connected. The authors of [19] then tile the entire plane with r-strips on lines:

$$y = k\left(\frac{\sqrt{3}}{2}+1\right)r \tag{8}$$

The r-strips are aligned for even values of the integer k and shifted horizontally $\frac{r}{2}$ for odd values of k, as illustrated in Figure 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. Additional sensors are placed along the y-axis to establish connectivity among nodes in different r-strips, (the shaded disks in Figure 6 (b)).
For every odd value of the integer k, two sensors are placed to establish connectivity between every pair of r-strips at:

$$\left[0, k\left(\frac{\sqrt{3}}{2}+1\right)r \pm \frac{\sqrt{3}}{2}r\right] \tag{9}$$

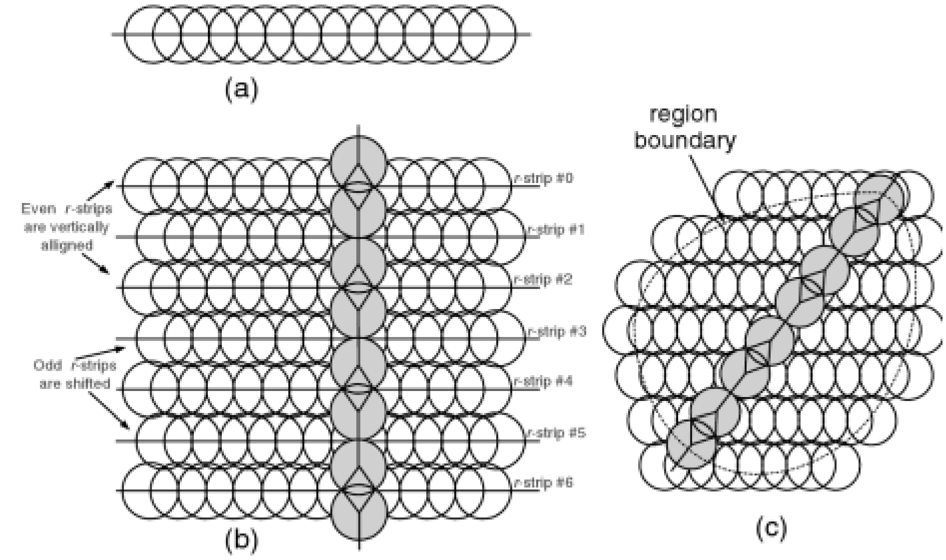


Figure 6: A r-strip: Illustration of the placement algorithm in a plane and a finite size region

An additional vertical strip is added along the y-axis to achieve the connectivity in the case of infinity region, and in the finite region. The strip for connectivity may not be vertical; it is placed in the angle so that it intersects all the horizontal r-strips. The intersection points need to be inside the monitored region [18]. In [19], authors generalize their scheme for the case where points of interest are to be covered rather than the whole area. However, unless the base-station is mobile and can interface with the WSN through any node, establishing a strongly connected network is not essential in WSNs since data are gathered at the base-station. Therefore, ensuring the presence of a data route from a node to the base-station would be sufficient, and fewer nodes can be employed to achieve network connectivity than the presented approach would use. In addition, vertically placed nodes or diagonal r-strips can become a communication bottleneck since they act as gateways among horizontal r-strips, which may require the deployment of more sensors to split the traffic [7].

4. SIMULATION RESULTS

In this section, simulations of different sensors placement strategies within a specific object are performed. The room size dimensions $50\ m \cdot 19\ m \cdot 4\ m$, with a flat ceiling and the average fire risk is observed. It is assumed that there are no physical barriers that influence sensors deployments. The aim is to choose the type of smoke detectors deployment, which achieves the highest possible coverage and the longest network life after fire ignition with the least number of sensors. It is desirable, therefore, to find the optimal deployment of sensors, so that full coverage and long life can be achieved using minimum number of sensors. The network lifetime is defined as the time until all nodes have been failed. As long as one sensor is alive, a stream of information about the location and spread of the fire will be provided.

For this purpose, we consider three deployment strategies: grid, triangular, and strip. It is also assumed that there are no physical partitions and barriers in the monitored field that may affect the deployment process and the operation of sensor networks. Ionization smoke detector type 1, whose activation threshold is 3:28 %/m of obscuration, is used for the simulation purposes.

4.1. Grid placement

Area of the rectangular room of dimensions $a \cdot b = 50 \cdot 19$ has $950\ m^2$. Approximately, the required number of detectors is achieved using Eq. (5): $n = \frac{950}{100} = 9.5$. As the number of detectors must be an integer, $n = 10$ is adopted, so two rows parallel to the longer side of the room with five detectors in each row make an optimal sensor placement. The width of the room is divided by the number two to obtain distance lines because, in this application configuration, the width of the room contains a distance between rows and two rows distance from the wall (Eq. (4)). Therefore, $d_2 = \frac{19}{2} = 9.5\ m$ and $d_3 = 4.75\ m$. Mutual detector distance is calculated by the length of the room, which is divided by five because it contains four distances detector - detector (d), and two wall - detector distance (d_1). So, $d = \frac{50}{5} = 10\ m$. The farthest distance from the nearest detector can be checked in the following way:

$$d_{11} = d_{22} = 0,5\left(d_2^2 + d^2\right)^{1/2} = 0,5\left(9,5^2 + 10^2\right)^{1/2} = 6,9m \le 7,5m$$

Smoke sensor placement, 2D and 3D view of the room and sensors are presented in Figure 7 and in Figure 8.

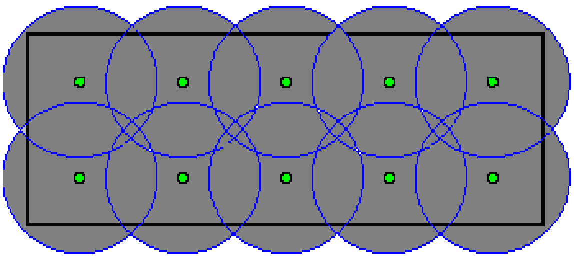
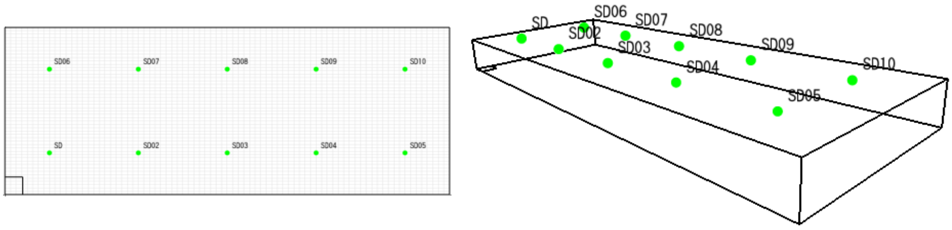


Figure 7: Smoke sensor grid placement (10 detectors)



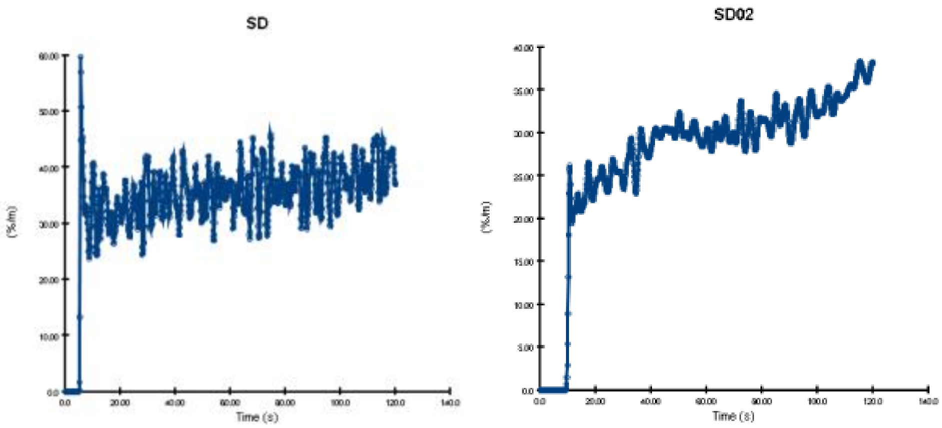
(a) 2D (b) 3D

Figure 8: View of the room, the fire source and smoke detectors' distribution

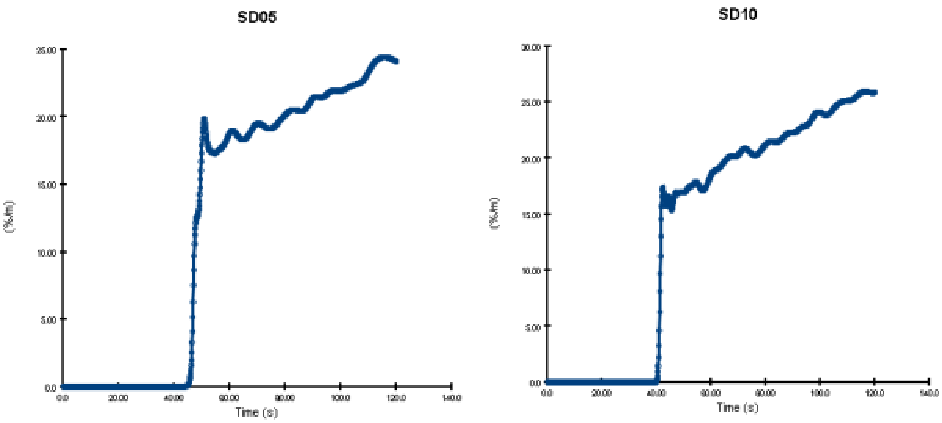
Pyrosim software tool [20] was used for simulation purposes. Figure 9 shows development of fire and smoke in 65th seconds from the fire ignition.

Figure 9: Development of fire and smoke in 65th seconds from the fire ignition

Smoke detector responses in the presence of fire are shown in Figure 10.



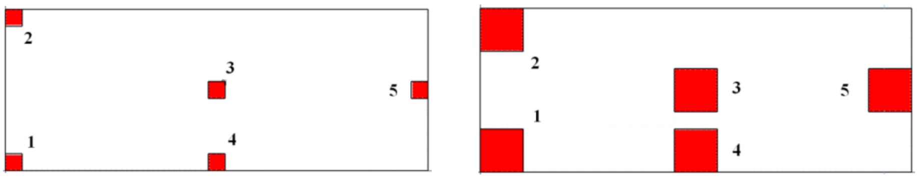
(a) Smoke sensor SD (b) Smoke sensor SD02



(c) Smoke sensor SD05 (d) Smoke sensor SD10

Figure 10: Smoke detector responses: two nearest and two farthest sensors from fire source

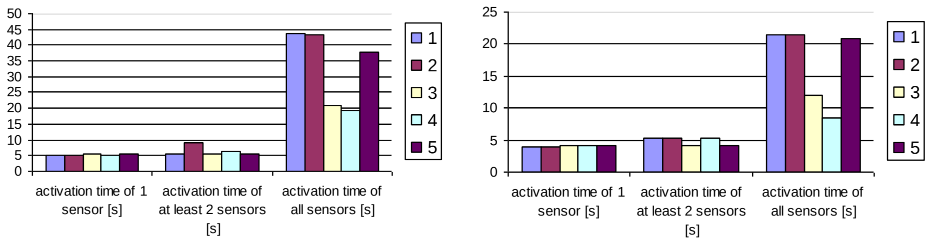
For the simulation purpose, five different positions of the fire source, and two fire source sizes are considered (Figure 11).



(a) 2 m x 2 m (b) 5 m x 5 m

Figure 11: Fire source positions and sizes

The worst case, when the fire is localized at the farthest distance from the detector, is also observed. The activation time of one sensor, activation time of at least two, and activation time of all the sensors (activation time of the last (farthest) sensor) are shown in Figure 12.



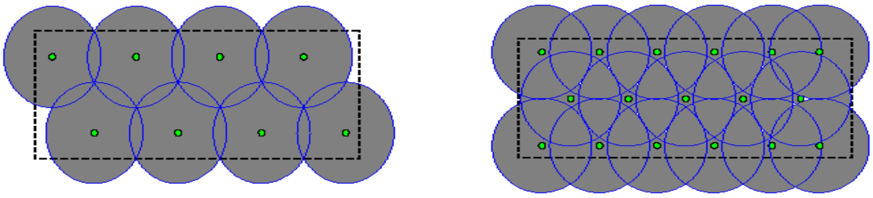
(a) 2 m x 2 m (b) 5 m x 5 m

Figure 12: Response times for grid smoke sensor placement for two fire source sizes placed on five different positions

From Figure 12 (a) and (b), it can be concluded that smoke sensors' response time is shorter if fire source size is larger.

4.2. Triangular placement

Smoke sensors have the sensing range r of 7.5 m (as it shown in Figure 3. (b)). An equilateral triangle whose edge's length is given by Eq. (7) should be formed. But in the case of the rectangular room whose dimensions are given above, full coverage can't be achieved (Figure 13 (a)).

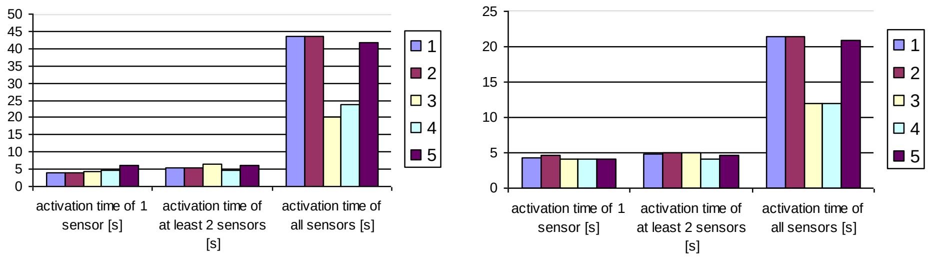


(a) 8 sensor (b) 17 sensors

Figure 13: Smoke sensors' triangular deployment

Thus, the triangle length is reduced by reducing the sensing range of smoke sensor from 7.5 to 5 m. 100% coverage is achieved with $d = \sqrt{3} \cdot r = \sqrt{3} \cdot 5 = 8.65\ m$, but the number of sensors increased from 8 to 17 (Figure 13 (b)).

Response times of smoke sensors for the deployment strategy in case of smaller and larger fire sources are presented in Figure 14. Just like in the previous case, smoke sensors' response time is shorter if the fire source is larger.



(a) 2 m x 2 m (b) 5 m x 5 m

Figure 14: Response times for modified triangular smoke sensor placement for two fire source sizes placed on five different positions

4.3. Strip placement

According to r-strip deployment strategy, presented in 3.3., for a given room, proposed smoke sensors' deployment is shown in Figure 15.

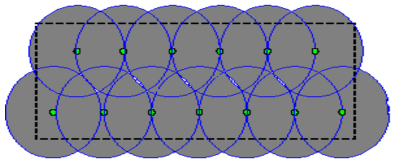
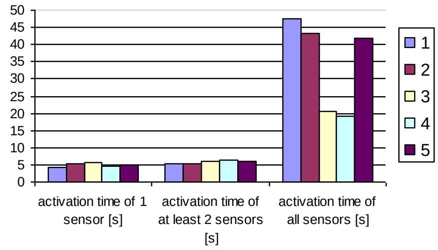
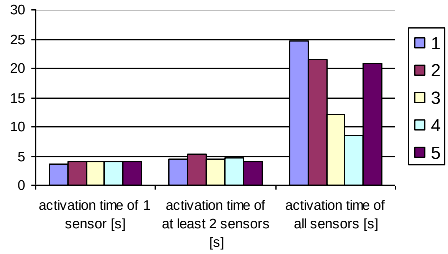


Figure 15: Smoke sensors' r-strip deployment (13 detectors)

Using this deployment strategy, 100% coverage is achieved. Response times of smoke sensors for the deployment strategy in case of the smaller and the larger fire sources are presented in Figure 16.



(a) 2 m x 2 m



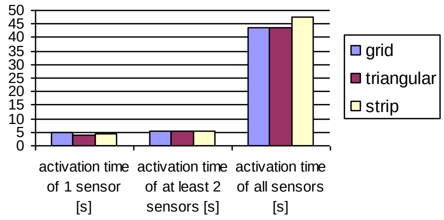
(b) 5 m x 5 m

Figure 16: Response times for r-strip smoke sensor placement for two fire source sizes placed on five different positions

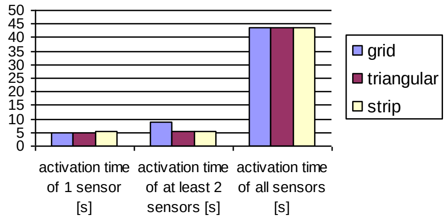
5. COMPARATIVE ANALYSIS

In this chapter, a comparative analysis of response times of the three considered placement strategies, depending on the size of fire and the locations, is performed.

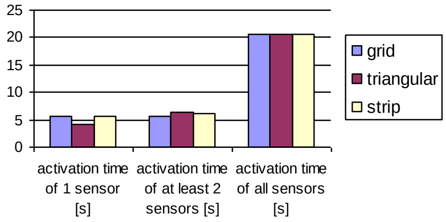
Figure 17 presents the obtained simulation results in the case of smaller fire source (2 m x 2 m). Figure 17 (a) shows that for the fire source position „1“ triangular deployment has the shortest activation time of one sensor, while strip deployment has the longest activation time of the last (farthest) sensor. For fire source position „2“, grid deployment has the shortest activation time of one sensor, but the longest activation time of at least two sensors. Activation time of the last (farthest) sensor in all three deployment strategies is equal for fire source position „2“ (Figure17 (b)) as for fire source position „3“ (Figure 17 (c)), where triangular deployment generates the shortest activation time of one sensor, and grid deployment generates the shortest activation time of at least two sensors. Figure 17(d) shows that for fire source position „4“, triangular deployment generates the shortest activation time for one and for at least two sensors, while at the same time, it has the longest activation time for all sensors, which makes it the best choice in this case. For fire source position „5“, whose results of activation time are presented in Figure 17 (e), strip deployment shows the best performances. Figure 17 (f) presents average values of activation times for the three deployment strategies.



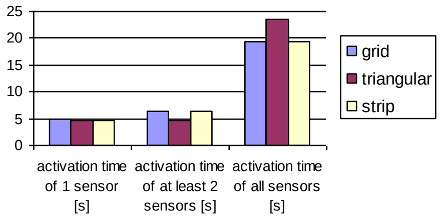
(a) fire source position “1”



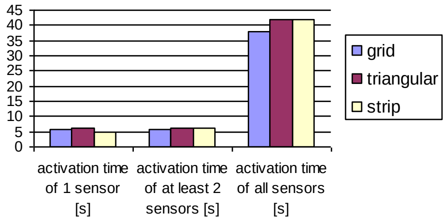
(b) fire source position “2”



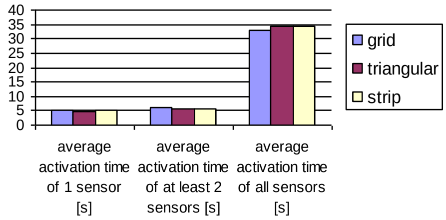
(c) fire source position “3”



(d) fire source position “4”



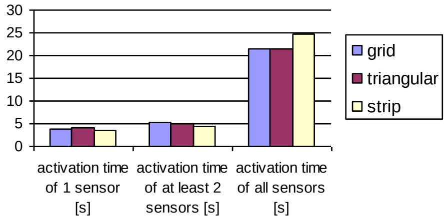
(e) fire source position “5”



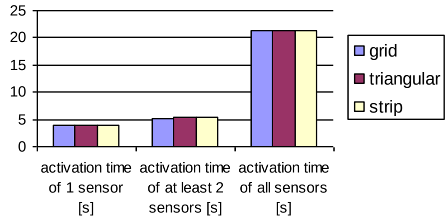
(f) Average activation time

Figure 17: Response sensors’ times for five proposed fire source positions and average activation time for fire source size 2 m x 2 m in a case of three proposed placement strategies

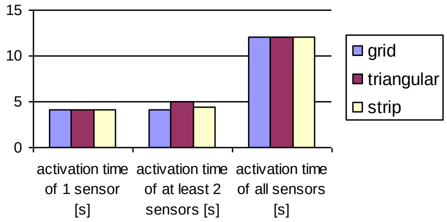
Figure 18 shows the obtained simulation results for larger fire source size (5 m x 5 m). It can be noted that the activation time decreases as the fire size increases. Figures 18 (a), (b) and (c), for fire source positions „1“, „2“ and „3“, respectively, show that strip deployment has the best performance. Triangular deployment is the best for fire source positions „4“(Figure 18 (d)), while grid and strip deployment generate equally good performances for fire source positions „5“(Figure 18 (e)). Figure 18 (f) presents average values of activation times for the three deployment strategies in case of larger fire source size. It can be seen that there is no significant difference among them in case of activation times, but strip deployment has slightly better performances compared with grid and triangular.



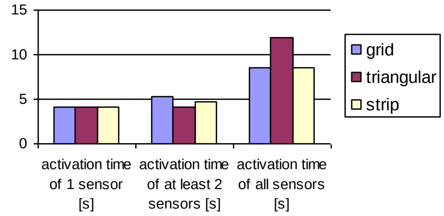
(a) fire source position “1”



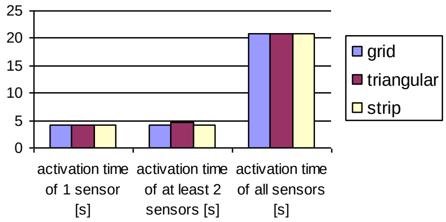
(b) fire source position “2”



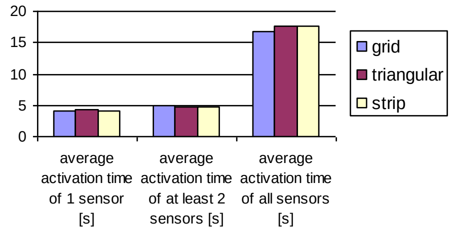
(c) fire source position “3”



(d) fire source position “4”



(e) fire source position “5”



(f) Average activation time

Figure 18: Response sensors’ times for five proposed fire source positions and average activation time for fire source size 5 m x 5 m in a case of three proposed placement strategies

5. CONCLUSION

There is no significant difference among performances of the deployment strategies for fire size 2 m x 2 m if performance evaluation is done based on the following criteria:

- the shortest activation time of at least two sensors (to eliminate false alarm possibility in the case of only one sensor activation) and
- the longest activation time of the last (farthest) sensor (as long as the time until last sensor’s failure is longer, it is possible to receive data from the sensor about the conditions in the room).

Triangular and strip deployment strategies have slightly better performances when compared to the grid. In case of larger fire source size (5 m x 5 m), according to the criteria defined above, the strip deployment strategy has the best performances, but again there is not a significant difference among considered deployment schemes.

Thus, the crucial criterion when choosing adequate deployment strategies in both cases lies on the number of used sensors and the percent of achieved coverage.

If the number of sensors would be crucial, then the grid deployment scheme is the best choice. If sensor's price is not a determining factor, in the considered case, strip deployment strategy represents a compromise between the obtained activation times, network lifetime, achieved coverage, and the number of used sensors.

Simulations performed in this paper confirmed that there is not a single approach to the design and the deployment of sensor networks today. Choice of the deployment strategy, which is the first step in forming any WSN, depends on applications, requirements, design goals, and physical characteristics of the monitoring area.

Directions for a future work may include considering the involvement of fuzzy logic in order to find a new, optimal sensor placement scheme.

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