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A NOVEL APPROACH TO MEASURING NODE AND ENERGY UNIFORMITY FOR THE OPTIMAL ASSIGNMENT OF DIRECTIONAL SENSORS[*]

M. HOSEINI,[**] M. DEHGHAN AND H. PEDRAM

Dept. of Computer Engineerin, Amirkabir University Tehran, I. R. of Iran
Email: mojtabahoseini@aut.ac.ir

Abstract– One of the prevalent methods to increase the network lifetime is to develop the uniformity in the sensor node distribution and load balancing. The existing criteria to calculate the uniformity are only able to locally or globally measure the uniformity of sensor distribution in the network. In this paper, a new criterion is proposed for the uniformity measurement of sensor distribution. The criterion can calculate the both global and local uniformity in various levels of node distribution. In addition, using the model of sensing area of each sensor, this criterion has been generalized for the uniformity of sensors energy distribution in the network via calculating the uniformity of sensor node distribution. In order to assess the performance of the proposed criterion, a set of sensor distribution patterns has been utilized; also, the uniformity calculation results of these patterns have been studied. Then, a method for the sensor assignment has been proposed in a network, in which sensor nodes have the possibility of rotation and a coverage area is selected. This method enhances the energy distribution uniformity in the network. The comparison is finally provided among the perceived results to show an acceptable performance of the proposed method.

Keywords– Uniformity measurement, global uniformity, local uniformity, directional sensor networks, uniformity maximization

1. INTRODUCTION

Directional Sensor Networks (DSNs) typically consist of numerous nodes. Each node is equipped with directional sensors such as video cameras, processing ability, wireless communication, and relatively limited energy resources, which are distributed in the network area [1]. Deterministic distribution and regular deployment of sensors in the network is often neither feasible nor practical [2]. Generally, sensors are distributed in the sensor network randomly. According to their applications and applied methods, the distribution of sensors can be uniform as Gaussian, Poisson, and so on. In the directional sensor networks, sensors have a limited field of view [3] and their angle can normally modify horizontally [4, 5]. Thus, they could select their coverage area in such a way that energy is distributed uniformly in the entire network region. A uniform sensor node distribution in the wireless sensor network would lead to better and more equitable expenditure of energy in nodes. Consequently, an appropriate criterion to estimate the useful lifetime of the network is uniformity in the network topology. Moreover, it is more likely to cover a desirable area with fewer nodes in a network with the uniform sensor distribution [6]. Uniformity has been defined in some works as the average local standard deviation of the distances between neighbor nodes. Also, it should be noted, this criterion produces some unacceptable results in the measurement of global uniformity.

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[**]Corresponding author

In this paper, first, a new criterion is introduced for evaluating the distribution uniformity of nodes throughout the network either locally or globally. Instead of the global uniformity that is computed from information of the local uniformity, the Local uniformity is measured by a distributed and an efficient algorithm with minimum communication between neighbor sensor nodes. This is an important reason for computing the local uniformity. Furthermore, the calculation criterion of the uniformity of the node distribution in the network is generalized to calculate the uniformity of the node energy distribution. For this aim, the sensing area model for every single sensor has to be considered as well. In order to evaluate the performance of this criterion, a set of sensor distribution patterns has been proposed. Each pattern is significantly different from others in terms of local and global. Additionally, the uniformity and intuitively of this pattern will be shown to prove the uniformity can be evaluated accurately by using this criterion. It is important to note that in the case of equal energy of the sensor nodes and uniform distribution of nodes, the energy distribution has no uniform distribution in the network area. Also, regions in the center area usually have more energy than regions in the boundaries of the network. An algorithm has been presented to calculate the uniformity of the node distribution in the network in a variety of levels (including global and local) with different scales of regions. This algorithm can measure the local uniformity as distributed and scalable. Based on the information of local uniformity, the algorithm hierarchically calculates the middle uniformity and general uniformity as well. In the following, these sensor nodes have been distributed in a network randomly so they have a specific fixed position, also, they can rotate and alter their sensing coverage angle. Here a method has been proposed to increase this uniformity of energy distribution. Furthermore, this algorithm can do the sensor assignment by different levels of uniformity.

Our contributions in this paper are to meet the goal of prolonging network lifetime, which can be summarized as: 1- Uniformity measurement of the geographical distribution of nodes in multi granularity levels from the local uniformity to the global uniformity instead of the other works in this context which usually concentrate on only one level. 2- Uniformity of energy distribution in regions of the network area is measured again in the multi granularity level. Meanwhile, the assignment of sensors energy to energy of the network regions has been little studied in the other researches. 3- Introducing a distributed and hierarchical algorithm for computing uniformity. 4- Introducing a distributed and hierarchical sensor assignment algorithm for the uniformity maximization.

The organization of this paper is as follows:

In the next section, the accomplished researches in this field are reviewed. A criterion is proposed to measure the uniformity of the node distribution in section 3. It is utilized to present an algorithm for the calculation of uniformity in various levels from the local to global uniformity. In the fourth section, the criterion of uniformity measurement is generalized in order to measure the uniformity of energy distribution instead of the node distribution. In section 5, a sensor assignment algorithm is proposed using the uniformity criterion of energy distribution. In the first step, two models of omni-directional and directional sensor coverage are attended. In addition, the sensors rotational ability is considered. Also, a new method is proposed to enhance the uniformity of energy distribution in the network by consideration of the outcome results of the mentioned issues. This method is able to assign sensors to the network regions in such a way that the energy of the network regions is uniformly distributed. The simulation and performance evaluation of the proposed algorithms are described in section 6. Finally, Section 7 is dedicated to the conclusion and suggestions for future researches.

2. RELATED WORKS

The uniform energy consumption in the network has been considered in many articles as a solution to prolonging the lifetime in the network. Studying the performed works in this field shows there are various methods that may be applied for the uniform load distribution and uniform energy consumption in the wireless sensor networks, such as time scheduling, selection of active sensors [7], traffic control, and routing [8]. Based on [9], several methods have been studied for k-coverage boundary problem. Therefore, the application of uniform energy consumption criterion has ended in the best response and it has increased the network lifetime.

In addition, a transmission distance is applied to adjust transmitter energy in wireless sensor networks [10]. To balance the energy consumption, low and high energy sensors are used for communication between near and far distances, respectively.

Furthermore, the existing nodes in the network are divided into several independent sets in such a way that each set could cover the whole network area [7]. A weighted coefficient is attributed to these sets in accordance with the available energy in the set. In order to deal with the coverage issue in each stage, a sensor set is utilized that has a higher amount of energy. Therefore, the constant energy consumption will help to increase the network lifetime.

According to the opinion of Lee et al [11], to balance energy consumption, a set of generated topologies should be used instead of a single given topology for the network during communication between sensor nodes. Each topology is applied on data collection cycles. Therefore, the energy consumption is balanced in the time domain to induce feasibility for the load distribution through various routes (spatial load balancing) as well (temporal load balancing).

All the sensors are able to move in a network for the uniform distribution, so the idea of moving nodes from the regions with the high-density node distribution to the low-density ones can be used. There is a method for inventing sensors deployment in an idea of spreading molecules in physics as well [12]. For this purpose, assuming that there is no global information from the network, an algorithm, called Self-Deployment by Density Control (SDDC), is presented to create a balance between sensors density. Some specifications of this algorithm are provided: simultaneous movement of several sensors, distributed performances, local calculation, and self-deployment. A distributed algorithm has been proposed in [6] for self-deployment of the moving sensors for applying the idea of the repulsion force between charged atoms. The efficiency criteria of this algorithm are as follows: coverage, uniformity, time, the passed distance by nodes and the time of algorithm convergence. Furthermore, the presented algorithm has been compared with an algorithm that includes a node deployment based on the simulated annealing. The uniformity criterion has been defined as the uniform deployment of node positions in the network. According to the sensors coverage area with the aim of k-coverage of targets, the number of sensors that could cover that area is calculated based on each part of the coverage area. The purpose of studying this issue is to realize whether or not it would be possible to cover all the given points with at least k sensors [13].

In the directional sensor networks, added to all the above-mentioned methods, the uniform energy consumption could be controlled in the network for using the sensors rotational capability for sensing the area selection. Moreover, in video sensor networks the energy consumption of sensing is independent to the distance and the presence or absence of targets, also the distance of targets does not have any effect on the energy consumption. In a video sensor, maximum distance of sensing is limited by which targets can be observed with minimum resolution. By aid of these capabilities, high-energy sensors can be applied on coverage of several near and far areas. Use of this capability is one of the innovative issues in this article.

The uniformity or non-uniformity of the node distribution extensively influences the following issues: the utilization of node energy, the coverage probability, the connectivity and the network lifetime. Some samples of the node distribution and uniformity maximization application in the network can be observed in [14-17]. Also, various criteria have been defined to measure the uniformity of sensor distribution. Based on the uniformity criterion, a variety of methods have been presented including distributed and centralized methods to measure the uniformity. Chang et al [9] believe the sensor network area has been partitioned into a set of small equal-sized parts. In each part, number of available sensors is counted and saved in the weighed grid matrix (WGM). The value of WGM for each region is applied as the sensor selection criterion in such a way that sensor distribution would end in more uniformity. The size of these parts is very small as the sensor located in each part can cover that area.

In [18], a very simple model has been applied to measure the global uniformity of sensor distribution in the network. The network area has been split into four equal regions and the uniformity is explained in terms of number of sensors in each region based on the quality of uniformity in three levels of good, intermediate, and weak.

- Good distribution: There are four states: a) At least two sensors are positioned in each region. b) Size of the largest area with no sensor is (maximum) ¾ of the whole area. c) Sensors are not centralized in the center or edges. d) The length to width of low-density areas is not larger than 2 to 1.
- Intermediate distribution: There are three states: a) At least one sensor is positioned in each region. b) Size of the largest area with no sensor is (maximum) equal to the whole area. c) The length to width of low-density areas is not larger than 3 to 1.
- Weak distribution: The remained states are categorized in this segment.

In [15], several criteria are shown for the uniformity measurement of sensor distribution in the network region (such as distance-measure index, area-ration index, clustering index, and U-measure index). Each of them is able to describe the uniformity of sensor distribution in the network. However, each may encounter difficulties in some special conditions. For instance, the U-measure criterion is determined with the following equations.

$$U = \frac{1}{N}\sum_{i=1}^{N} U_i \tag{1}$$

where:

$$U_i = \left(\frac{1}{K_i}\sum_{j=1}^{K_i}\left(D_{i,j} - M_i\right)^2\right)^{1/2} \tag{2}$$

The variables in these equations are as follows:

N: Total number of nodes
K_i: Number of neighbors of the i^{th} node
$D_{i,j}$: the distance between the i^{th} and j^{th} node
M_i: the average distance between the i^{th} node and its neighbors
U_i: local uniformity, it is calculated in each sensor for its neighbors
U: Total uniformity that is centrally calculated based on local uniformities

Only neighbor nodes in the communication radius are used to calculate local uniformity. It is presumed that communication radius is twice the sensing radius. Therefore, the uniformity criterion is a local criterion and every node is only able to access the local information. The low value of U_i s and U would reflect the uniform distribution in the network. The major problem of this criterion refers to the fact that if all neighbor nodes are in the same distance from the node, U will be zero and the highest amount uniformity is achieved, i.e, in the mentioned equations, the average distance value does not affect uniformity. For example, in case all of the nodes are located on each other with zero distance, it is still mistakenly interpreted as the maximum uniformity. It should be added that although this criterion is suitable for small-sized areas, it does not perform properly in the entire network area [15].

In [19], some known mathematical criteria for measuring the uniformity of distribution is introduced and compared from different aspects, including: Chi-square test proposed by Pearson (1900), Kolmogorov-Smirnov test (1939), Cramer-von Mises test (1952), Berrendero, Cuevas and Vazquez-

Grande (2006), and Justel, Pena and Zamar (1997). In the following a criteria is introduced that can measure the uniformity of distribution of a random multivariate variable. The criterion is as shown bellow:

$$G_{k(x_1,x_2,\dots,x_1,)}=\frac{(n+1)^k}{(n+1)^{k-1}}\sum_{i_1=1}^{n+1}\sum_{i_2=1}^{n+1}\cdots\sum_{i_k=1}^{n+1}\left[\prod_{j=1}^{k}\left(X_{(i_1)j}-X_{(i_1-1)j}\right)-\frac{1}{(n+1)^k}\right]^2 \quad (3)$$

where $X_n=\begin{bmatrix}x_{n1}\\x_{n2}\\x_{n3}\\\vdots\\x_{nk}\end{bmatrix}$ is a random sample from a k-dimensional population distribution.

The range of Eq. (3) is in [0-1]. It is equal to zero for the total uniform distribution and to one for the total non-uniform distribution.

3. THE CRITERION FOR MEASUREMENT OF THE UNIFORMITY OF NODE DISTRIBUTION

In this section, a criterion is shown for measurement of the uniformity of the node distribution in the network. It is able to calculate the uniformity in different levels. These levels could measure the local uniformity of very small-sized areas as well as the global uniformity of the whole network.

According to the following equation, assume that the network area has been divided into N equal-sized regions. Total number of nodes in the network is Ns. Ns_i, ($1\le i\le$N) is number of available nodes in each region. The uniformity criterion is obtained from unbiased variance ($var(Ns_i)$).

$$U(N,N_s)=\left(\frac{1}{\left(\frac{N-1}{N_s}\right)^2\operatorname{var}(Ns_i)+\frac{N-1}{N}}-\frac{1}{N-1}\right)\times 100\% \quad (4)$$

In the appendix 1, the selection reasoning and calculation method of this equation are expanded. In this equation, the minimum uniformity value is equal to zero for entirely non-uniform distribution and its maximum value is 100% for completely uniform distribution.

a) The definition of local and global uniformity

Local uniformity: in order to maintain local uniformity, node distribution in small regions of the network has to be uniform. The most appropriate small region can be regarded in the area under the node communication coverage.

Global uniformity: node distribution should be uniformed in large regions of the network. A region whose area is a quarter of the whole network can be considered as the large region.

In Fig. 1, the network regions divisions can be seen in three levels. In Fig. 1a small regions are suitable for local uniformity measurement. Figure 1c is appropriate for the global uniformity measurement of large regions. Fig. 1b is good for regions with a size in between.

The algorithm of the uniformity measurement:

In this section, an algorithm is proposed to calculate the uniformity in different levels. Its parameters and notations are described in detail as follow:

- l, $1\le l\le L$ is the area of uniformity calculation. l=1 refers to the largest region and $l=L$ relates to the smallest one. L is the maximum number of levels for uniformity calculation.
- $N_{l,j}$: Number of sensors in the l^{th} uniformity level and j^{th} region area, where $1\le l\le L$, $1\le j\le 2^{2l}$. Note that number of regions in the l^{th} uniformity level is equal to 2^{2l}. For example, in the largest partitioning, the network is divided into four regions and $N_{1,1}$ *to* $N_{1,4}$ refers to number of sensors inside each region for uniformity calculation of the largest region in the network.

The proposed algorithm stages are provided below.

1. Estimation of number of levels for L uniformity calculation: If the area of the smallest and largest regions are considered equal to communication radius of nodes and a quarter of the entire network area, respectively, for number of uniformity calculation levels, the equation below can be regarded:

$$L = \left\lfloor \frac{1}{2} \log_2 \left(\frac{s_a}{s_c} \right) \right\rfloor \tag{5}$$

In this equation, S_a is the network area and S_c is the coverable area for each sensor.

2. Division of the network into small regions with low granularity
3. Count number of nodes in every region for l=L
4. Uniformity calculation of node distribution obtained from Eq. (4)
5. Merger of the network regions: creating areas with the higher granularity and calculating number of nodes in each region based on the number of included nodes.

$$N_{l,j} = \sum_{k=4j-3}^{4j} N_{l+1,k} \quad , 1 \le l < L \tag{6}$$

6. Repetition of stages 4, 5, and 6 in order to reach the highest granularity in the network

In Fig. 3, the flowchart of the algorithm is shown. Based on the Table 1 and Fig. 2, the results of uniformity measurement are represented using Eq. (4) on several samples of the node deployments in the network. It's observed that the numerical results are compatible with real observations and using introduced criteria leads to acceptable results for the local, middle and general uniformity evaluations.
More details regarding the parameters and the perceived results will be presented in the simulation section.

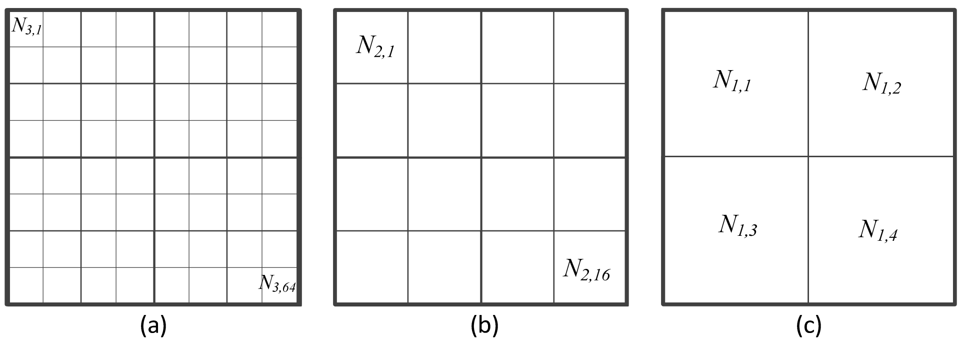


Fig. 1. The network regions classification in three levels: (a) low granularity regions for local uniformity measurement, (b) medium granularity, (c) high granularity regions for the global uniformity measurement

Table 1. Uniformity criterion for several samples node distribution in the deployment samples of Fig. 10

Sensor distribution patterns in Fig.10	a	b	c	d	e	f	g	h	i	j	k	l
l=1 Global uniformity	100	99.0	52.2	80.4	68.6	92.2	97.7	45.7	33.5	46.3	20.9	0
l=2 Middle uniformity	100	95.8	48.2	77.4	66.9	69.4	41.4	30.9	20.7	47.2	12.1	0
l=3 Local uniformity	100	82.9	44.5	65.9	58.4	36.3	28.6	23.3	16.9	43.4	9.6	0
Uniformity from Eq.(2)	0	0.15	.36	.46	.63	.29	.48	.53	.61	.21	.19	0.09
Uniformity from Eq.(3)	0.12	0.21	.45	.51	.69	.43	.62	.68	.63	.39	.27	0.07

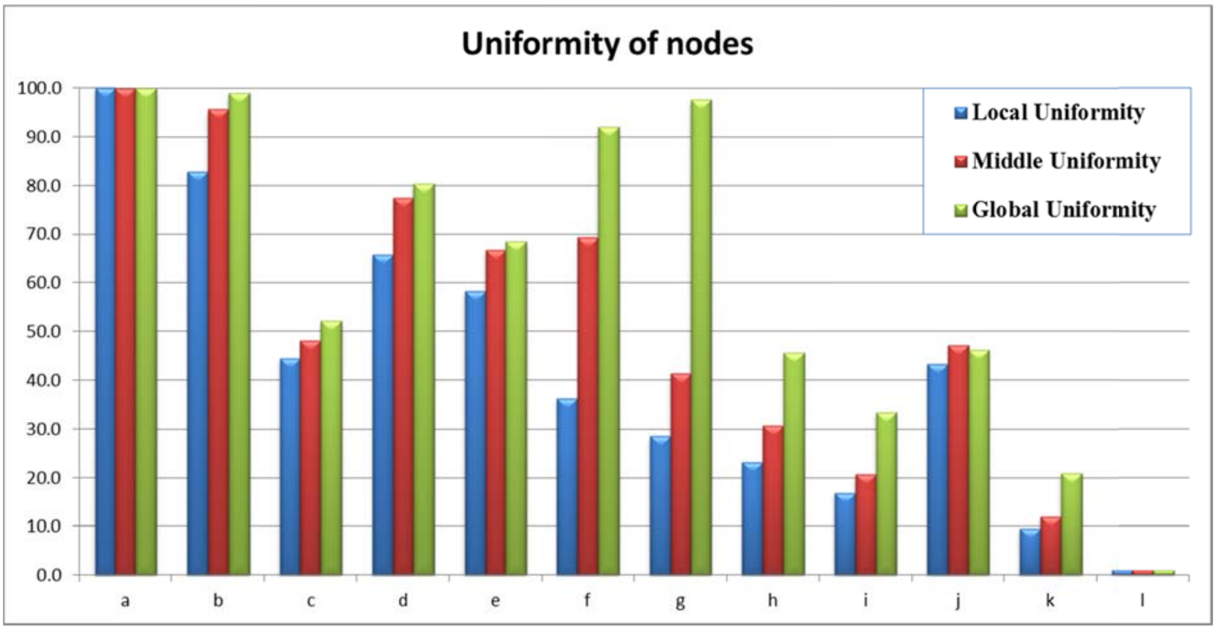


Fig. 2. Uniformity value of node distribution in the deployment samples of Fig. 10

4. THE MEASUREMENT CRITERION OF THE ENERGY DISTRIBUTION UNIFORMITY IN THE NETWORK

In this section, the proposed criterion for measurement of the uniformity of node distribution is generalized to become a measurement criterion for the uniformity of energy distribution in the network. For this purpose, assume that the network area is divided into N equal-sized regions. Areas can be in square, rectangle, triangle or honeypot form. The mentioned shapes have two features: First, they can cover the whole network without any hole. Second, the smaller areas can together make similar larger areas, which are different just in size. According to its sensing area, every sensor can cover one or several regions. The sensing area can be regarded based on the two prevalent models of directional and omni-directional [20]. Through application of the following equations, the coverage possibility of each network region is studied using each of these two sensing models.

The sensing area model of each sensor can be expressed as $((x_s,y_s),R_2)$ for omni-directional sensors and $((x_s,y_s),R_1,R_2,b,\varphi)$) for directional ones [21].

In this model, (x_s,y_s) are the coordinates of sensor S in a two-dimensional space. R_1 is the minimum radius of vision, in which a sensor like visual sensor is able to clearly observe. R_2 is the maximum sensing radius, φ the angle of sensor from the horizontal axis and b is sensor angle of view. In order to locate a region with the center coordinates (x_i,y_i) inside the sensing radius of a sensor, the following equation has to be true.

$$R_1 \le d \le R_2 \tag{7}$$

In this equation, d is the distance between sensor and region center and is obtained from the following equation.

$$d = \sqrt{(x_s - x_i)^2 + (y_s - y_i)^2} \tag{8}$$

If a region is located in a sensor angle of view, the following inequality holds true.

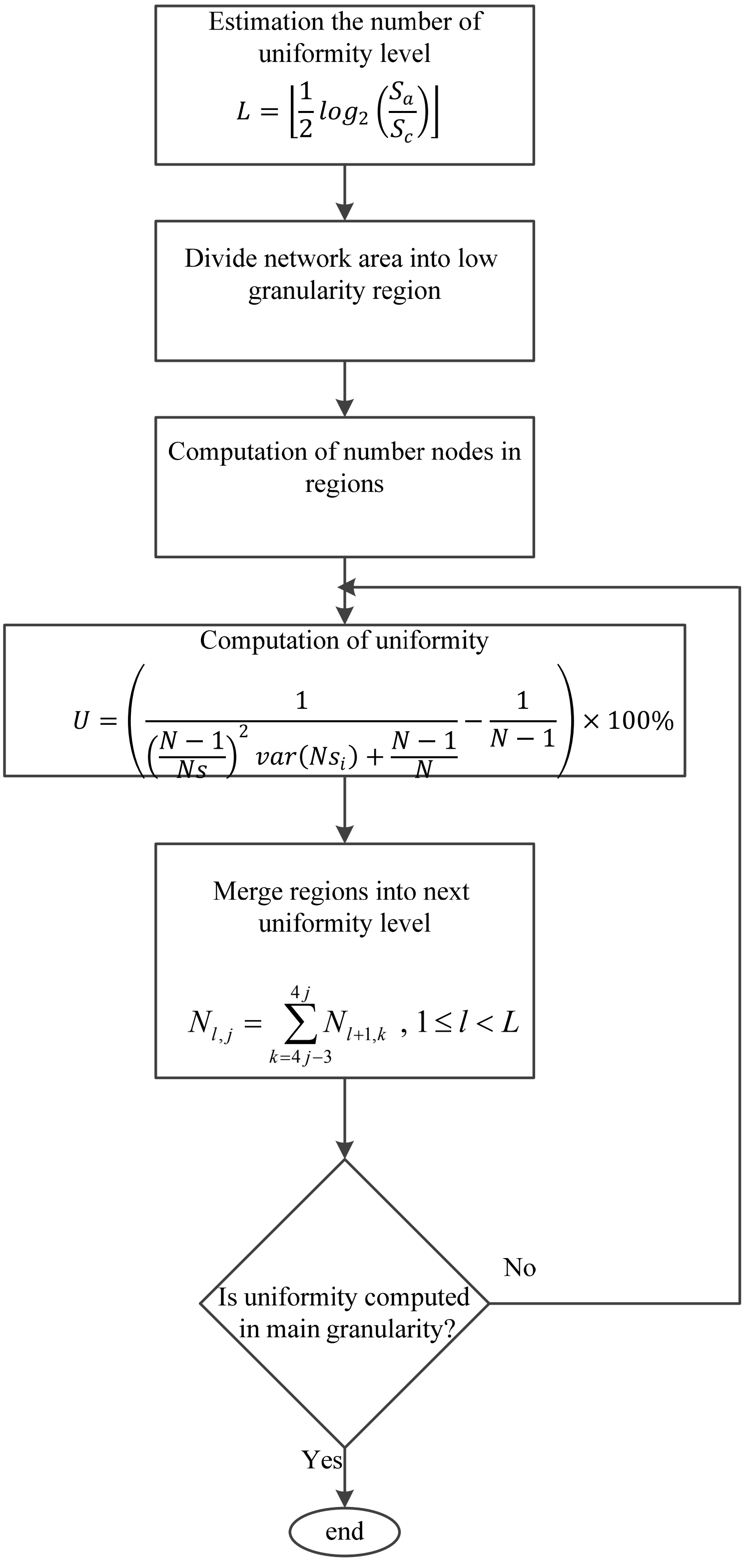


Fig. 3. Uniformity calculation flowchart

$$\varphi - \frac{b}{2} \le \theta \le \varphi + \frac{b}{2} \tag{9}$$

In this equation, θ is angle of the region center from the sensor. It is gained from the following equation.

$$\theta = \tan^{-1}\frac{y_s - y_i}{x_s - x_i} \tag{10}$$

In a case where omni-directional sensor model is considered, it is sufficient that the condition $d \le R$ for a region's coverage with a sensor would be true.

With these two models, the energy amount of each region is calculated from total energy of nodes, which could cover that region. If the set $S_i=\{s_{ij}\}$ would be a set of sensors that cover the i^{th} region, ES_j is the j^{th} sensor energy, and ER_j is the j^{th} region energy. Then, for each region's energy, the following is true:

$$ER_i = \sum_j ES_j \quad \forall s \in S_i \tag{11}$$

The sum of all regions energy is equal to:

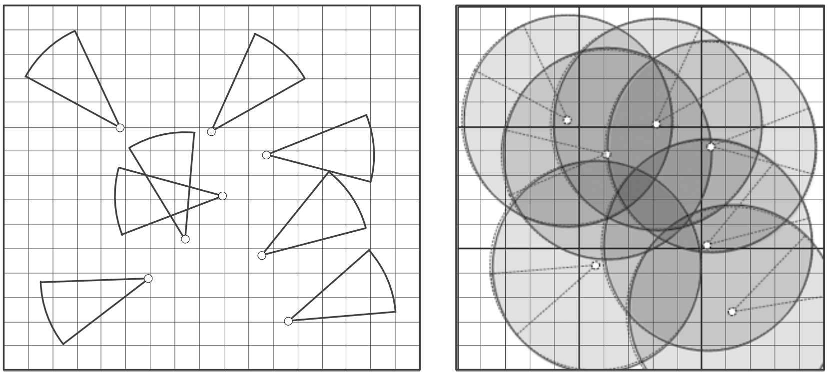
$$E_R=\sum_j ER_i \tag{12}$$

It should be noted that in Eq. (12), since each sensor may cover more than a single region, the energy of that sensor would influence the entire covered regions. Thus, sum of all regions energy is unequal to sum of all sensors energy.

As a result, Eq. (4) is written as follows to describe the uniformity criterion of the energy distribution in the network.

$$U(N, E_R) = \left(\frac{1}{\left(\frac{N-1}{E_R}\right)^2 \operatorname{var}(ER_i) + \frac{N-1}{N}} - \frac{1}{N-1} \right) \times 100\% \tag{13}$$

In Table 2, using Eq. (13), uniformity measurement results of omni-directional sensors energy distribution is observed on some samples of node deployments



(a) (b)

Fig. 4. The area covered by sensors to measure the areas energy. (a) Directional sensing area, (b) Omni-directional sensing area (or potential coverage area of the directional sensor with rotational capability)

Table 2. Uniformity criterion of omni-directional sensors energy for several samples of node deployments

Sensor distribution patterns in Fig. 10	a	b	c	d	e	f	g	h	i	j	k	l
l=3 Local uniformity	97.8	96.4	49.4	78.2	64.2	88.6	58.0	37.4	30.1	54.8	16.3	1.5
l=2 Middle uniformity	98.9	97.9	50.3	80.7	65.4	94.1	66.2	40.5	33.0	56.1	17.7	0.4
l=1 Global uniformity	99.6	99.2	53.9	84.6	65.4	97.9	99.4	51.3	42.1	56.0	26.2	1.0

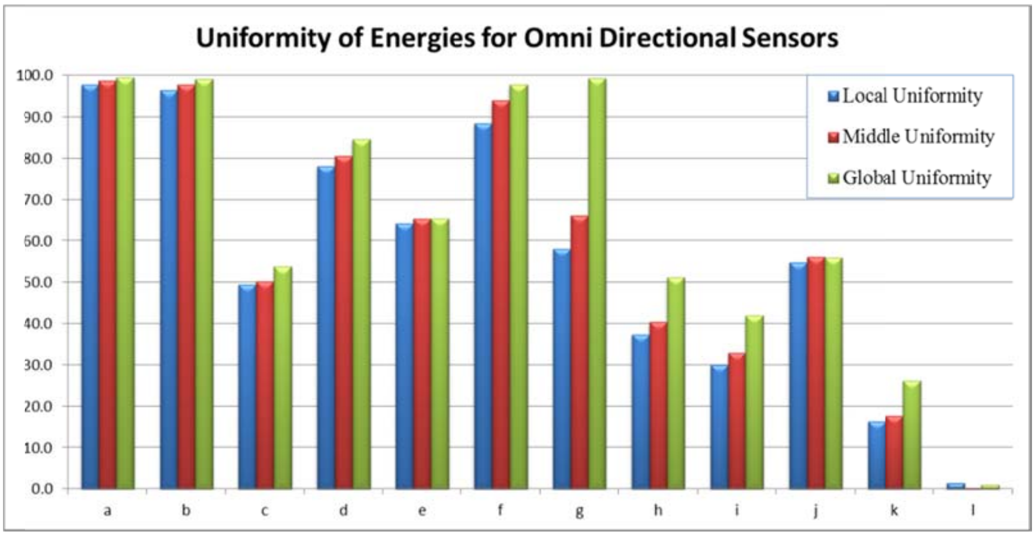


Fig. 5. Uniformity criterion of omni-directional sensors energy of sensor distribution patterns from Fig. 10 (according to Table 2)

5. SENSORS ASSIGNMENT TO THE NETWORK REGIONS VIA SENSORS DIRECTION ADJUSTMENT

In this section, using an algorithm presented for the uniformity calculation in the network, a method is presented to adjust the sensors angle of view and the sensors assignment to various regions. It is provided to maximize the energy distribution uniformity in a network with directional sensors. For this purpose, the network is initially divided into regions with the highest granularity. At first, based on the Fig. 4(a), it is presumed that sensors are directional, also, each sensor can choose its coverage area via rotation or changing its angle of view. In the proposed algorithm, the uniformity of energy distribution is firstly calculated with respect to omni-directional model for a sensor. It specifies the regions that every sensor could potentially cover. The sensor assignment is initiated from the region that has the lowest potential energy. Then, it is repeated for the regions with the higher energy until all the sensors are assigned into the entire regions. These stages can be repeated again for a level with the lower granularity. Each region has to be divided into smaller ones, and then, sensors assignment should be repeated in smaller regions. As a result, it can be expected that the uniformity of energy distribution would be provided for different levels in the network. Based on the Fig. 6, the flowchart of the sensor assignment algorithm to the network regions can be observed.

The stages of the proposed algorithm are as follows:

1. Network Splitting into large regions with the high granularity
2. Measurement of the uniformity of energy distribution in various levels based on the presented algorithm in the section 4, with the consideration of omni-directional model for sensor. Consideration of this model for the sensor would enable us to calculate each sensor's energy for the regions that are potentially coverable by that sensor.
3. Sensors assignment based on the uniformity level and energy amount of each region: sensors are initially assigned to regions that potentially have the lower amount of energy.
4. Repetition of stage 3 until all the sensors are assigned to all the regions. The repetition times are equal to the number of sensors.
5. Splitting the network regions: the creation of areas with lower granularity
6. Repetition of stage 2 to 5 for each of the new regions and re-assignment of each region's sensors to its sub-regions. The repetition times are equal to the number of granularity levels.
7. Adjustment of sensors angles to cover the region that they are assigned to.

According to Fig. 6, the flowchart of the algorithm is shown. In Fig. 7, an instance of algorithm application can be observed. In Fig. 7a, the initial coverage and in Fig. 7b, the coverage after the sensor assignment to the network regions and adjustment of sensors angle of view can be seen. In the following, the simulation results and performance evaluation of the presented methods will be studied.

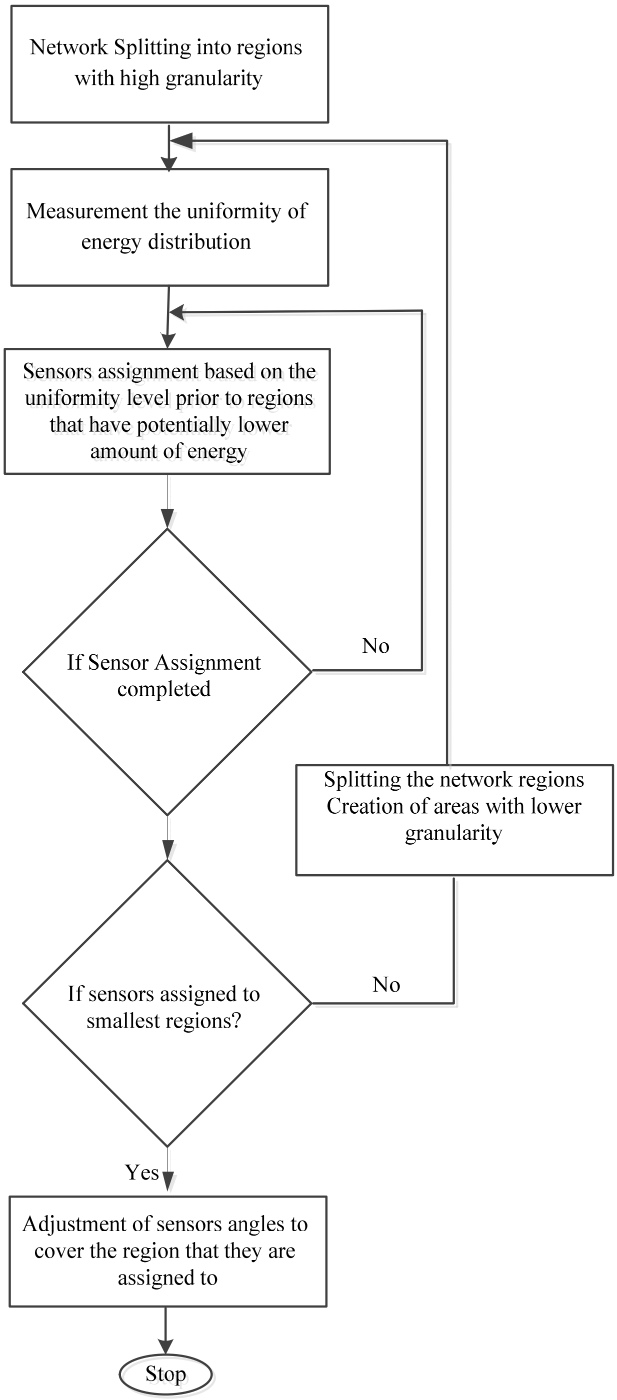


Fig. 6. Algorithm flowchart of sensor assignment to the network regions

6. SIMULATION AND PERFORMANCE EVALUATION

In this part, the details related to criteria simulation and proposed algorithms are shown. For the simulation, it is presumed that network dimensions are 1000×1000 and 100 sensors are distributed with regard to the patterns of Fig. 10 [22]. The uniformity in the network has been calculated in three different levels. Global, middle and local uniformity, in which the network area has been split into the 2×2, 4×4,and 8×8 regions, respectively. The sensors constant parameters are $R_1=5$ ، $R_2=300$ ، $b=30^\circ$. Energy of sensors is assumed equal. The value of φ is random in the beginning. After application of the sensor assignment algorithm, the value will be calculated. According to the Fig. 10 the Sensor distribution is performed and for each pattern, a trial set of 10 repetitions is generated, also the average value of outputs (obtained from repetitions) will be provided as the result.

The results of uniformity measurement of the sensor distribution in the network are represented in Table 1 and Fig. 2. It can be seen that Fig. 10a has the maximum uniformity in all three levels and Fig. 10*l* has the minimum uniformity. With study of the other panels of this figure, and numerical comparison of the results of the uniformity calculation, it is shown that the presented criterion can demonstrate an acceptable range of uniformity in all three levels. For instance, in Fig. 10f and 10g, the local uniformity is in the low level and the global uniformity is in the high level. Figure 10f has higher middle uniformity in comparison to Fig. 10g. This is proven through the perceived results as well. In addition, the other calculated results from the other works mentioned in Eq. (2) and Eq. (3) are compared. It can be intuitively seen that the two criteria lead to the same result as the local uniformity measurement criteria. For example, uniformity value for Fig. 10l is similar to Fig. 10a, and shows maximum uniformity, which indicates their weakness.

In Table 3 and Fig. 8, the level of the uniformity of energy distribution is represented before and after the algorithm application for the sensor assignment. Additionally, the improvement rate of uniformity on the patterns of Fig. 10 is shown. It can be seen that in the entire states, the level of improvement has been significant and in the maximum case, it has been 47%.

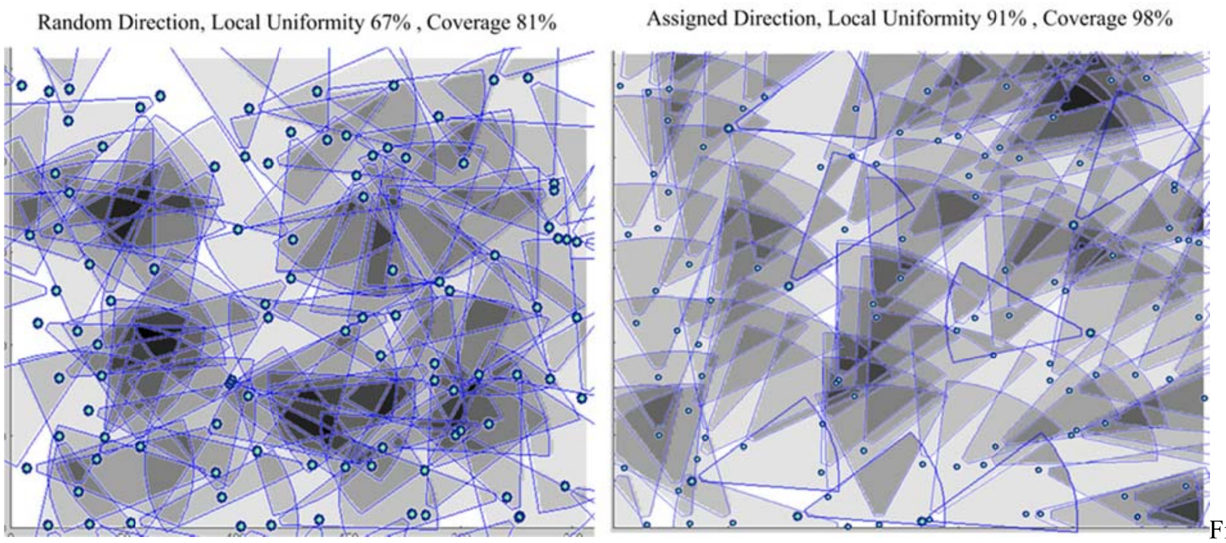


Fig. 7. Sensor assignation to region. (a) The initial direction of sensors is random. (b) Angle adjustment to increase the regions energy uniformity

Added to the uniformity of energy distribution in the network, the coverage extent of the network regions is another criterion that can be utilized for performance of the proposed algorithm. For this purpose, the proportion of regions (that have been covered by at least one sensor) to the total number of regions has been measured as the coverage rate. In Fig. 7, a sample of real coverage with the application of the sensor assignment algorithm to the network regions can be observed. In Table 4 and Fig. 9, the coverage rate of the network regions before and after the sensor assignment algorithm have been provided by a value of coverage improvement. In the whole states, the coverage improvement is again considerable and in the most appropriate conditions, it is obtained up to 32%.

Table 3. The uniformity of energy distribution level before and after application of the sensor assignment algorithm, by uniformity improvement rate

Uniformity	Distribution patterns in Fig.10	a	b	c	d	e	f	g	h	i	j	k	l
Local	Initial deployment	70.2	71.4	60.5	66.9	59.4	68.0	64.0	58.0	56.9	60.0	53.6	9.2
	After assignment	83.3	88.5	89.2	88.3	83.9	86.8	86.5	80.0	79.7	77.4	61.5	9.2
	improvement%	18.6	24.0	47.2	32.0	41.2	27.6	35.1	37.9	40.0	29.0	14.7	0.3
Middle	Initial deployment	79.5	80.2	64.7	74.4	65.6	76.6	70.5	62.0	62.3	66.5	57.1	9.0
	After assignment	86.0	92.1	92.9	93.0	88.2	91.0	90.0	85.0	82.8	81.1	65.0	9.9
	improvement%	8.2	14.9	43.5	24.9	34.5	18.7	27.6	37.0	33.0	22.0	13.8	9.8
Global	Initial deployment	89.0	94.1	72.3	87.7	73.1	90.2	85.2	67.7	69.6	72.2	67.0	6.0
	After assignment	94.6	94.3	96.8	96.7	90.7	94.1	92.4	89.0	87.5	85.1	69.5	6.1
	improvement%	6.3	0.2	33.9	10.3	24.0	4.4	8.5	31.6	25.6	17.8	3.8	2.0

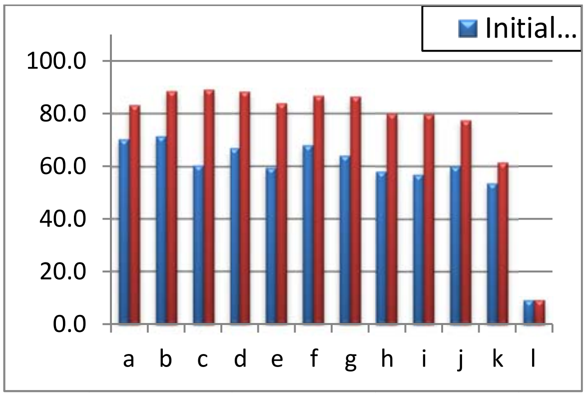


Fig. 8. Local uniformity of directional sensors energy after sensor assignment to the region (local uniformity in Table 3)

Table 4. Coverage rate of the network regions before and after sensor assignment algorithm by value of coverage improvement

Distribution patterns in Fig.10	a	b	c	d	e	f	g	h	i	j	k	l
Initial deployment	82.4	79.8	74	79.3	70.9	79.6	81.1	77.2	69	73.6	62.8	10.8
After assignment	89.4	93.3	97.4	95.5	93.8	95.5	92.6	91.5	86.5	88.5	72.8	11.4
improvement%	8.5	16.9	31.6	20.4	32.3	20.0	14.2	18.5	25.4	20.2	15.9	5.6

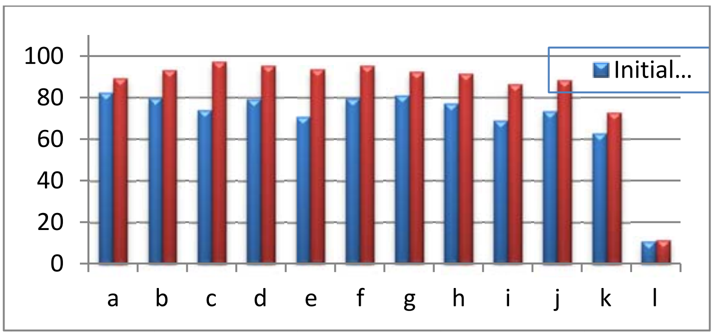


Fig. 9. Coverage rate of the network regions before and after sensor assignment algorithm by value of coverage improvement

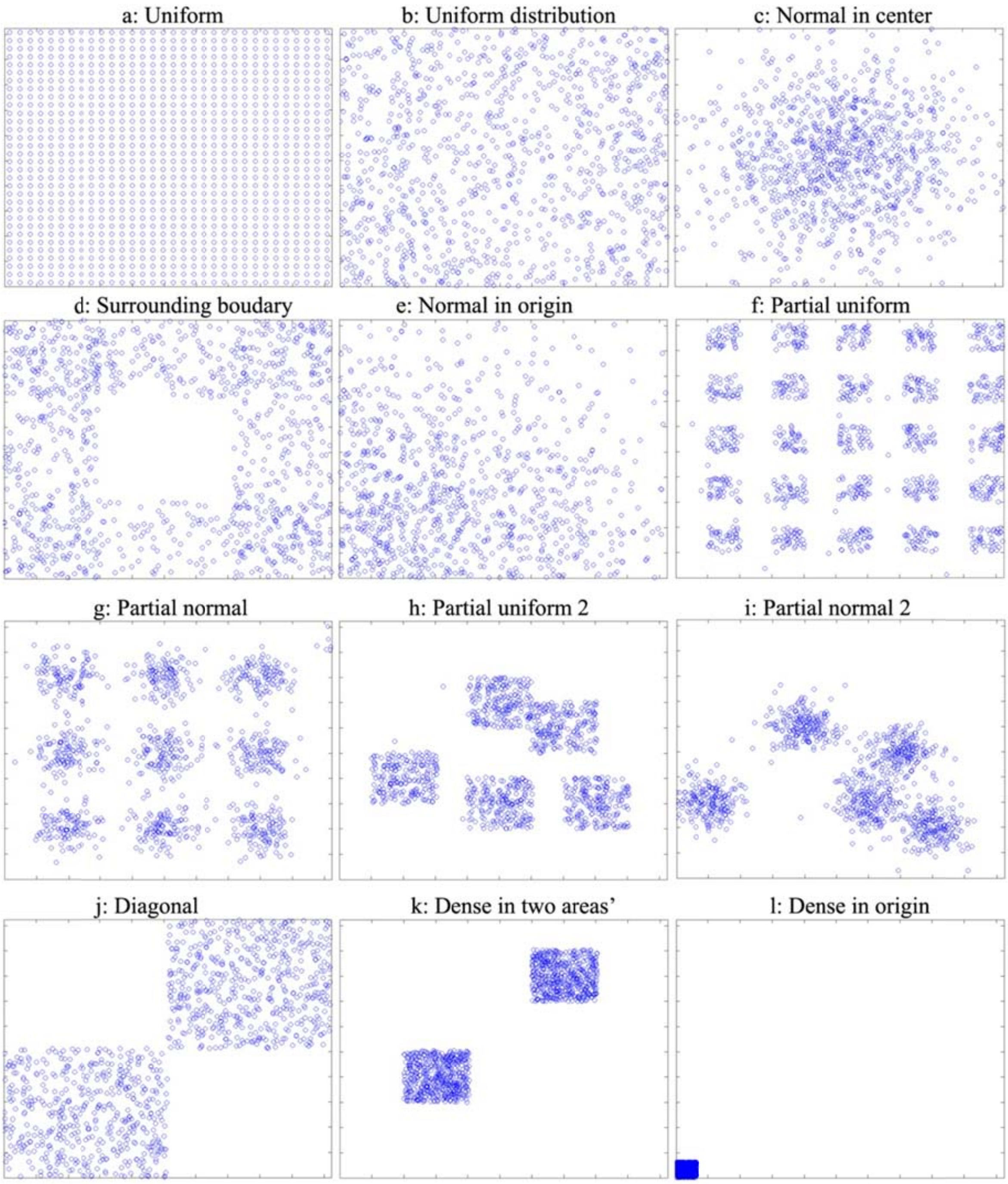


Fig. 10. A set of sensor distribution trial patterns in the network [22]

7. CONCLUSION

In this article, a new criterion for the uniformity measurement of the sensor distribution was presented. This criterion can calculate the uniformity in various levels from the global uniformity with the large regions to the local uniformity with the small regions (around the nodes sensing radius). In the next stage, this criterion was generalized for calculation of the uniformity of the sensor energy distribution in the network. Also, a method was proposed that increased the uniformity of energy distribution in the network through sensors assignment to the network regions via rotating and changing of the angle of view of sensor nodes. In order to assess the performance of this criterion and the proposed methods, a set of sensor distribution patterns was utilized in the network. The gained results represent that the proposed criterion for the uniformity measurement is properly able to measure the local, middle, and global uniformity on the sensor distribution patterns. Moreover, applying this method for the sensor assignment, the uniformity of energy distribution of the network, and the network regions coverage has been extensively increased. In future works, the proposed method can be altered in such a way that sensors are assigned with respect to the network requirements, including targets distribution density in the network regions. Additionally, the distribution of nodes in the network area can be researched in the future works based on the acceptable level of the uniformity of the node. According to the numbers of the covered nodes in the network, the sensor distribution and describing the relation between application types can be found as well. Solving the region assignment to targets after the sensor assignment is another useful study. The parameters of target model such as: size, direction, speed, and other mobility of targets, can affect region assignment strategies.

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APPENDIX 1. THE CALCULATION METHOD OF UNIFORMITY FUNCTION

In order to innovate a suitable uniformity function, assume the following scenario. We assume that the network area is split into *N* region, also the total number of available nodes in the network is *Ns*. All the nodes are equally distributed in only *y* regions out of the total number of regions, y=1 reflects the most non-uniform type of distribution, in which all the nodes are located in one region. *y=N* is the most uniform type of distribution, in which all the nodes are equally split.

$$Ns_i = \begin{cases} \dfrac{N_s}{y}, & i \le y \\ 0, & otherwise \end{cases}$$

where $Ns_i, 1 \le i \le N$ is the number of available nodes in each region.

In this case, y value can be considered as the distribution uniformity criterion. The objective is to find a linear and an ascending function that provides zero and one (100% uniformity) for *y*=1 and *y*=*N*, respectively. This function is applied for the uniformity measurement in other conditions of node distribution in the network like the sensors distribution pattern shown in the Fig. 10. For this purpose, the node distribution variance based on the y is our starting point:

$$\mathrm{var}(y) = \frac{1}{N-1}\left(\sum_{i=1}^{N} Ns_i^2 - N \times \overline{Ns_i}\right) = \frac{1}{N-1}\left(y\left(\frac{Ns}{y}\right)^2 - N \times \left(\frac{Ns}{y}\right)^2\right) = \frac{Ns^2}{N-1}\left(\frac{1}{y} - \frac{1}{N}\right) \rightarrow$$

$$\mathrm{var}(y) = \frac{Ns^2}{N(N-1)}\left(\frac{N}{y} - 1\right)$$

Precise consideration of the variance function would explain why the function is non-linear and unable to appropriately differentiate the uniformity in different cases. Therefore, it is advised to apply a function of *var(y)* to make it linear. A simple form of this function is the reverse function of *var(y)*.

$$\mathrm{var}(y) = \frac{Ns^2}{N(N-1)}\left(\frac{N}{y} - 1\right) \rightarrow y = \frac{N}{\dfrac{N(N-1)}{Ns^2}\mathrm{var}(y) + 1} = \frac{1}{\dfrac{(N-1)}{Ns^2}\mathrm{var}(y) + \dfrac{1}{N}}$$

As far as the minimum and maximum value of y is 1 and N, respectively, in order to locate the uniformity function between zero and one, we apply a linear equation as shown below:

$$u = \frac{y-1}{N-1} = \frac{\frac{1}{N-1}}{\frac{N-1}{N_s^{\,2}}\operatorname{var}(y) + \frac{1}{N}} - \frac{1}{N-1} \rightarrow u = \frac{1}{\left(\frac{N-1}{N_s}\right)^2 \operatorname{var}(y) + \frac{N-1}{N}} - \frac{1}{N-1}$$

This is equation (3) addressed above. A brief study shows that this function's value for the completely uniform distribution ($var(y)=0$) is equal to $u=1$ and for the entirely non-uniform distribution ($var(y)=Ns^2$ / N) , the function value is zero.

In this regard, the U value for the two boundary states of fully uniform and non-uniform node distribution is as follows:

Fully uniform node distribution: in this case, the number of nodes in each region is equal to the average amount of nodes. Thus, $var(NS_i)$ is zero and U is equal to $\frac{1}{\left(\frac{N-1}{N}\right)} - \frac{1}{N-1} = 1$ (i.e. 100% uniformity is achieved).

Fully non-uniform node distribution: the most non-uniform type of distribution refers to a case that all the nodes are positioned in the only one region (e.g. the j^{th} region). In this case, the following are true:

$$Ns_i = \begin{cases} N_s, & i = j \\ 0, & otherwise \end{cases} \rightarrow$$

$$\operatorname{var}(y) = \frac{1}{N-1}\left(\sum_{i=1}^{N} Ns_i^2 - N \times \overline{Ns_i}\right) = \frac{1}{N-1}\left(Ns^2 - N \times \left(\frac{Ns}{y}\right)^2\right) = \frac{Ns^2}{N} \rightarrow$$

$$u = \frac{1}{\left(\frac{N-1}{N_s}\right)^2 \operatorname{var}(Ns_i) + \frac{N-1}{N}} - \frac{1}{N-1} = \frac{1}{\left(\frac{N-1}{N_s}\right)^2 \frac{Ns^2}{N} + \frac{N-1}{N}} - \frac{1}{N-1} = \frac{1}{\frac{(N-1)^2}{N} + \frac{N-1}{N}} - \frac{1}{N-1} = \frac{1}{\frac{(N-1)}{N}((N-1)+1)} - \frac{1}{N-1} = 0$$

Therefore, in Eq. (3), the minimum value of the uniformity variable is zero for the fully non-uniform distribution and its maximum value is equal to 1 for the fully uniform distribution. The variations of uniformity are linear in values in between.