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Coverage Analysis of Various Wireless Sensor Network Deployment Strategies

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Abstract: *Recent years have seen a developing interest in deploying large number of sensor nodes that coordinate in a distributed fashion on data gathering and analysing. These nodes can be deployed over a Wireless Sensor Network in random or deterministic fashion. While the random node deployment is preferred in many applications, if possible, other deployments should be investigated since an inappropriate node deployment can increase the complexity of other problems in Wireless Sensor Networks(WSNs) such as excessive energy consumption. Thus, we examine three competitors of node deployment for a sensor network: a regular hexagon based, a octagon-square based and a tri-beehive based tiling. We have taken a major performance evaluation measure namely coverage analysis for all the three sensor node deployment strategies*

Keywords: *Sensor Nodes, Deployment, Coverage Analysis, K-coverage, Sensing Radius*

I. Introduction

Many of us talks about our common sense but do we know what the technology has got for itself, it's the Wireless Sense. A Wireless Sensor Network consist of distributed sensor nodes to monitor physical or environmental conditions such as temperature, moisture, heat etc and to coordinately pass the recorded information for further processing. Each sensor node has several organs namely a radio transceiver with an internal antenna or connected with external antenna, a microcontroller for interfacing between sensor and energy source and energy source i.e. battery. Now days modern Wireless Sensor Networks (WSN) are bidirectional, also enabling control of sensor activity. The nodes communicate wirelessly and often self-organize after being deployed in an ad hoc fashion. Such systems can revolutionize the way we live and work.

The Wireless Sensor Networks (WSN)'s applications can be generally classified into target tracking and area monitoring. In the target tracking scenarios, we concern if we can trace the moving object accurately or not. The number of sensors and the position of sensors affect the performance and accuracy of tracking. In the area monitoring scenarios, we need to have enough sensors to avoid blind angle. Thus, it might seem as a solution that a denser infrastructure cause a more effective WSNs. However, if not deployed well, a denser network will lead to a larger number of packet collisions and traffic congestions. So, the efficiency and effectiveness of the Wireless Sensor Network (WSN) depends on the fact that how its sensor nodes have been deployed in the field. Some of the factors to explain the importance of the good deployment strategy for Wireless Sensor Networks (WSN) are discussed below:

- **Limited Energy:** A well-known characteristic is that wireless sensor nodes have limited energy and have difficult in recharging. According to the energy consumption model, the longer the transmitting range is, the more energy the wireless sensor nodes will consume. For energy saving, proper distance among sensors nodes is important for Wireless Sensor Network (WSNs). Transmitting by multiple hops path is usually better than by directly. The topology of WSNs affects the network lifetime considerably.

- **Transmission Jobs:** To extend the lifetime of WSNs, we usually regularly schedule sleep intervals for sensor nodes. Usually, multiple sensor nodes sensing similar data will need to aggregate them towards the source. Transmission jobs will cost a lot, if the WSN's don't have uniform sensing coverage.

- **Unprotected Areas:** The monitoring area is not usually protected, especially for military applications and other security related tasks. To prevent being invaded, deployment information is a good option to key management schema for WSNs, that is, deployment strategy affects the key schema for encoding and decoding the confidential information.

Thus, we have taken three different deterministic deployment patterns for Wireless Sensor Network (WSNs) namely a regular hexagon based, a octagon-square based and a tri-beehive pattern for sensor nodes deployment and analysed each of them on the basis of their average coverage provided in the application field.

II. Regular Hexagon Pattern

A grid-based deployment is considered as a good deployment in WSNs, especially for the coverage performance. There are several grid based designs like as unit square, equilateral triangle, regular hexagon etc. We have chosen the regular hexagon grid deployment pattern for the evaluation purpose.

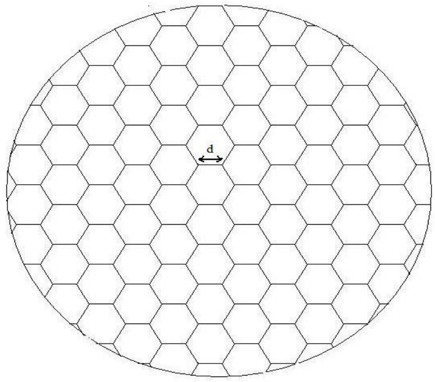


Fig (1) A regular hexagon based deployment pattern

A regular hexagon based node deployment pattern is depicted above in fig (1). Each of the sensor nodes are deployed on the intersection points of the grid in a considered circular field with radius, say R. The pattern within a circular field with radius R is assumed to be symmetric tessellations i.e. all the unit cells within the circular field have equal edge length d and thus equal area within each unit hexagon cell.

1.1. Sensing Range For Regular Hexagon Deployment Pattern

The Sensing Range, R_{sense} of the sensor nodes can be defined as the maximum distance up to which the nodes are capable to sense the or monitor the objects. The Sensing Range, R_{sense} varies in its values for various deployment patterns. The sensing range R_{sense} is assumed to be equal to the edge length say 'd' of the unit hexagon cell of the circular field shaped Regular Hexagon based deployment pattern. In fig (1), a grid deployment of n sensor nodes in a circular field is shown, where each of the n grid points hosts a sensor mote. The approximate length of a unit hexagon, d, can be calculated in the following way:

First, the approximate area of a unit hexagon with length d can be computed by dividing the whole area of a given field having radius R, with the number of cells, k.

Area of unit square cell = Whole Area of circular field / Number of cells in field (1)

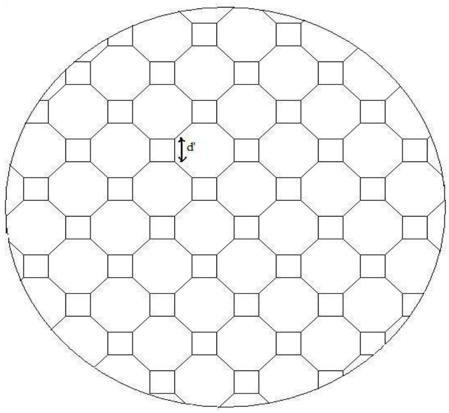
For regular hexagon based deployment pattern, the approximate value of k is (n/3 – 1). So, from the relation (1), we derive relation (2) for R_{sense}, the sensing radius or the sensing range for the regular hexagon based deployment pattern.

$$R_{sense} = \pi R^2 / (3\sqrt{3}/2)(n/3 - 1)$$

$$R_{sense} = \sqrt{(6\pi R^2 / 3\sqrt{3}n)} \quad (2)$$

III. OCTAGON-SQUARE PATTERN

Octagon-Square based deployment pattern for Wireless Sensor Network (WSN) is based on tiling also considered as tessellations. In octagon-square based tessellations we have regular octagons with their vertex surrounded with the squares. Both have same edge length say d'. The basic structure of octagon-square based deployment pattern is shown in fig(2).



Fig(2) Octagon-Square based deployment pattern

3.1 Sensing Range for Octagon-Square Deployment Pattern

In the similar way, like as we have used to find out the sensing radius, R_{sense} for the regular hexagon based pattern, the sensing radius for octagon-square based deployment pattern can also be calculated by dividing the whole area of the considered circular field with radius R with the number of unit octagon-square cells. The approximate number of cells, k for octagon-square based pattern is $(\sqrt{n}/2 - 1)^2$.

Thus, the sensing range R_{sense} calculated for Octagon-Square node deployment pattern is,

$$R_{sense} = \pi R^2 / (3+\sqrt{2})(\sqrt{n}/2 - 1)^2$$

$$R_{sense} = \sqrt{(2\pi R^2 / (3+\sqrt{2})n)} \quad (3)$$

IV. Tri-Beehive Pattern

Tri-Beehive deployment pattern for Wireless Sensor Network (WSN) uses triangle and hexagon in the two dimensional plane. The edge length for tri-beehive deployment pattern say d'' is considered to be symmetrical throughout the coverage field with radius R.

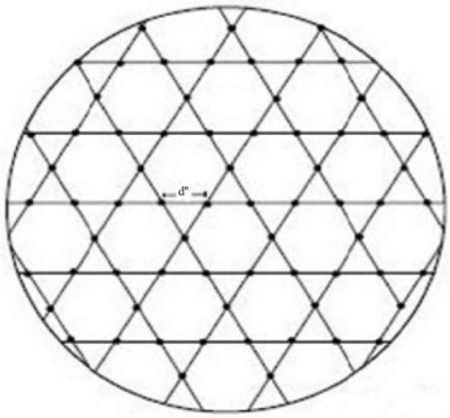


Fig (3) Tri-Beehive based deployment pattern

4.1 Sensing Range for Tri-Beehive Deployment Pattern

In the similar way, like as we have used to find out the sensing radius, R_{sense} above, the sensing range calculated for Tri-Beehive node deployment pattern is,

$$R_{sense} = \sqrt{(4\pi R^2 / 3\sqrt{3}n)} \quad (4)$$

V. Coverage

The term coverage in the respect for the Wireless Sensor Network(WSN) can be considered as the maximum range or area up to which the network is able to send or receive the data and also able to track the objects for monitoring them. In Wireless Sensor Network (WSN), the simple reason for checking coverage is to provide the high quality of information in the region of application. To fulfil the desired coverage of a region, adjusting the sensing range has its limitations due to the expensive energy consumption and restricted sensor node capabilities. Therefore, node deployment becomes very important. We have studied the K-coverage map for resolving the coverage issue which is the usual way of specifying conditions on coverage.

5.1 K-Coverage

A network is said to have k-coverage if every point in it is covered by at least k sensor nodes. If a particular point in the area which is being monitored by the Wireless Sensor Network (WSN) nodes is monitored by two sensor nodes, then that particular point of area is said to have 2-coverage.

A k-coverage map is drawn for the area to be analysed and the area is divided into different sectors based on the value of K for various points in the area of inspection.

5.2 Assumptions for K-Coverage

The K- coverage map, which is used to check all possible coverage areas and to analyze the relative frequency of exactly K-covered points Using the idea of the K- coverage map we measure the quality of coverage performance of all the three considered node deployment strategies.

There are certain assumptions which need to be made before proceeding further for the K- coverage maps for the Regular Hexagon deployment pattern, Octagon-Square deployment pattern and the Tri-Beehive node deployment pattern. Following are those assumptions:

- A disc-based sensing model is used for homogeneous nodes where each sensor has a maximum sensing range of the Sensing Radius, R_{sense}.
- The Sensing Radius, R_{sense}, is the same as the length of a unit cell namely d, d' and d''. Therefore R_{sense} is different for the regular hexagon node deployment, octagon-square node deployment and the tri-beehive node deployment pattern.
- A point is covered by a sensor node if it lies either within a disc of Sensing Radius, R_{sense}, or falls exactly at circumference of a disc shaped circular field undertaken.
- No boundary conditions are considered for the three of the patterns which seems reasonable for large-scale Wireless Sensor Network (WSN) conditions.

5.3 Average Coverage and Standard Deviation

The Average K- coverage or the weighted coverage can be computed to be provide the coverage capacity of all of the three deployment strategies. The average coverage is computed through following equation,

K- coverage * exactly K- covered points (%) / 100

For finding out the Standard Deviation in the coverage of each of the three strategies, it is necessary firstly to compute the sample variance through following method:

$$\sigma^2_{\text{weighted}} = \frac{\sum_{i=1}^{N} w_i \left(x_i - \mu^*\right)^2}{V_1} \quad (5)$$

$$\text{where} \quad V_1 = \sum_{i=1}^{n} w_i \quad (6)$$

Where

μ^* = is the weighted average or the average coverage

w_i = exactly K- covered points(%)

x_i = K- coverage (value of K)

Then, the Standard Deviation for the coverage will be the square root of the sample variance calculated in equation (5).

$$\text{Standard Deviation} = \sqrt{\sigma^2_{\text{weighted}}} \quad (7)$$

5.4 K-Coverage for Regular Hexagon Pattern Unit Cell

Fig (4) shows the unit hexagon cell for Regular Hexagon deployment pattern. In the regular hexagon cell, sensor nodes are placed at the vertices of the hexagon and their sensing range forms the intersected regions within the cell giving the k-coverage. As it is assumed that the sensing range, R_{sense} is equal to the edge length of a cell, a regular hexagon grid cell has exact 2-coverage, 3-coverage and 6-coverage regions.

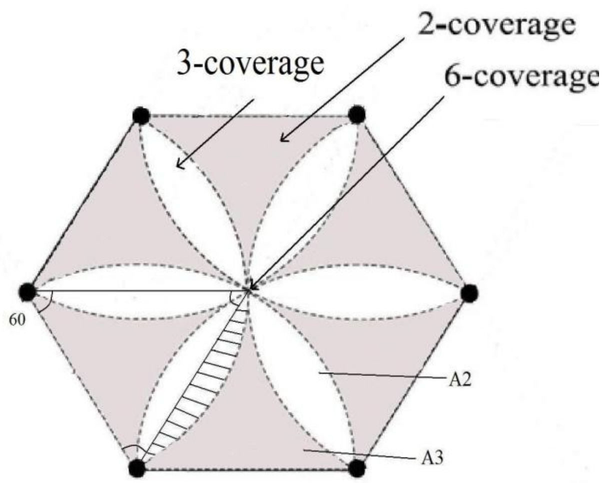


Fig (4) Regular Hexagon Cell K-coverage map

To compute the total area of exact k-coverage of a Regular Hexagon grid cell, we firstly need to find out the individual areas A2 and A3 shown in the fig (4).

Starting with the intersection area between two circles if the circumference of one circle passes through the origin of the other circle and vice versa,

$$A1 = [\,(4\pi - 3\sqrt{3}) / 6\,] * (R_{sense})^2 \quad (8)$$

Now, we know that internal angles in an equilateral triangle is of 60̊ , so area of sector with 60̊ angle is,

$$S = (60/360)\pi(R_{sense})^2 \quad (9)$$

Also, area of an equilateral triangle is,

$$T = \sqrt{3}/4*(R_{sense})^2 \quad (10)$$

Thus, the 3-coverage area i.e. A2 will be,

$$A2 = 2*(S - T) \quad (11)$$

Also, the 2-coverage area i.e. A3 will be,

$$A3 = (0.5*A1 - 2*A2) \quad (12)$$

The total 3-coverage will be six times of A2 and total 2-coverage will be six times of A3. The exact 6-coverage area, in which a single point is available for each regular hexagon cell is assumed to be zero (0) in a perfect Regular Hexagon deployment pattern.

5.5 K-Coverage for Octagon-Square Pattern Unit Cell

The octagon-square cell is illustrated in fig (5) which is a combination of a octagon and four squares. In a octagon-square unit cell, sensor nodes are placed on the vertices of the cell with symmetrical edge length corresponding to the sensing radius R_{sense}.

Inside an octagon, there are four possible coverage: 0-, 1-,2-,3-coverage and in each square there are 2-,3- and 4-coverage. Total areas of exact k-coverage for a Octagon-Square cell can be calculated by individually considering the 0-, 1-, 2-, 3- and 4-coverage areas.

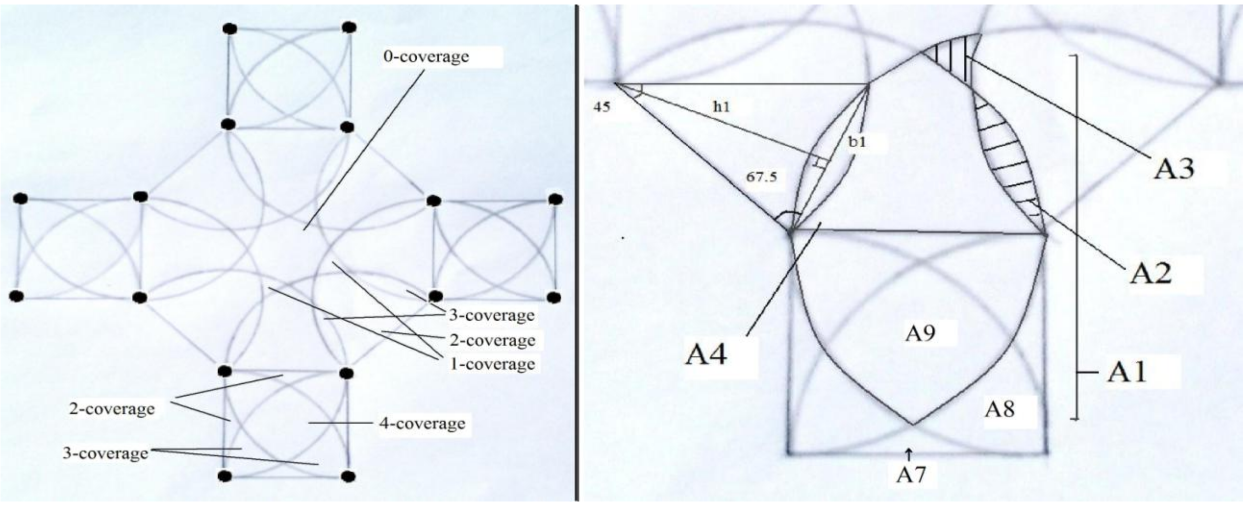


Fig (5) Octagon-Square cell k-coverage map

$$Oct = 2* (1+\sqrt{2})*(R_{sense})^2 \quad (13)$$

$$A1 = [(4\pi - 3\sqrt{3}) / 6] * (R_{sense})^2 \quad (14)$$

Equation (13) gives the area of a regular octagon and equation (14) gives the intersection area between two circles if the circumference of one circle passes through the origin of the other circle and vice versa.

According to fig (5), the area of sector with angle of 45^o and the area of triangular region within it will be as follows,

$$S = (45/360)\pi*(R_{sense})^2 \quad (15)$$

$$T = (R_{sense} * h1) / 2 \quad (16)$$

Where 'h1' is the height of the triangular region based on base length of triangle say 'b1' which can derived through equation (17) and (18).

$$h1 = \sqrt{(b1)^2 - (R_{sense}^2 / 4)} \quad (17)$$

$$b1 = 2* (\cos(67.5)*R_{sense}) \quad (18)$$

So, the 3-coverage and the 2-coverage i.e. A2 and A4 can be derived with equation (19) and (20) respectively.

$$A2 = 2 * (S - T) \quad (19)$$

$$A4 = (0.5*A1 - 2*A2) \quad (20)$$

The internal angle of a regular octagon is 135^o which gives the area of a sector of circle with angle of 135^o.

$$S1 = (135/360)\, \pi\, (R_{sense})^2 \quad (21)$$

Thus, the 1-coverage area A3 will be using equation (14),(19) and (21),

$$A3 = S1 - A1 + A2 \quad (22)$$

For the square part of the cell, the area between two circles, $x^2 + (y - r)^2 = r^2$ and $(x - r)^2 + y^2 = r^2$ is calculated.

$$A5 = (\pi - 2) / 2*(R_{sense})^2 \quad (23)$$

Now, we compute the area of the combination of 2- and 3-coverage, which is the difference of a quarter circle area and a half of area A1.

$$A6 = [(\pi R_{sense}^2 / 4) - 0.5A1] \quad (24)$$

Next the equation (25) is used to calculate the 2-coverage area near the border line of the square part of the cell.

$$A7 = [R_{sense}^2 - (\pi R_{sense}^2 / 4)] - A6 \quad (25)$$

Knowing A6 and A7 from equation (24) and (25), we calculate A8, which is one of the exact 3-coverage areas in equation (26).

$$A8 = A6 – A7 \quad (26)$$

The exact 4-coverage area is computed by using Equations (23) and (26) by the difference of A5 and two times A8.

$$A9 = A5 − 2*A8 \quad (27)$$

Thus, the total 0-,1-, 2-, 3- and 4-coverage in the Octagon-Square unit cell can be viewed from equation (28) to (32) using above equations respectively.

$$\text{0-coverage} = Oct – 8*(A2+A3+A4) \quad (28)$$
$$\text{1-coverage} = 8*A3 \quad (29)$$
$$\text{2-coverage} = (16*A7+8*A4) \quad (30)$$
$$\text{3-coverage} = (16*A8+8*A2) \quad (31)$$
$$\text{4-coverage} = 4*A9 \quad (32)$$

5.5 K-Coverage for Tri-Beehive Pattern Unit Cell

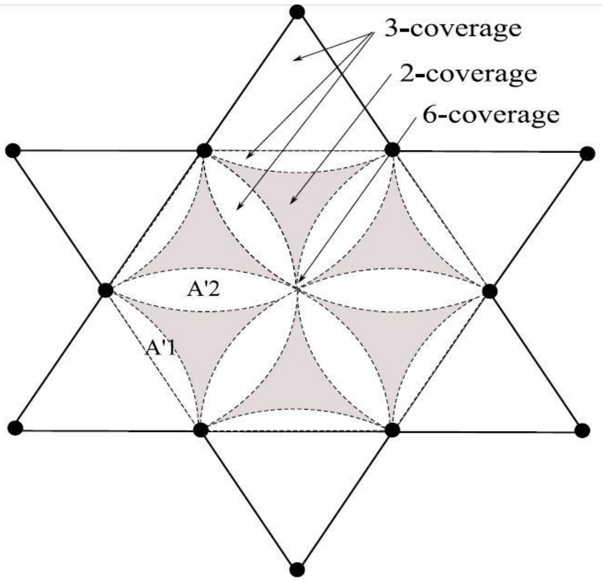


Fig (6) Tri-Beehive cell k-coverage map

The Tri-Beehive deployment cell is illustrated in fig (6), which is the combination of six equilateral triangles and one regular hexagon. Total areas of exact k-coverage for a Tri-Beehive cell can be calculated by individually considering the 2-, 3- and 6 coverage areas.

For the K-coverage, we have the areas of the regular hexagon and an equilateral triangle with edge length R_{sense} in equation (33) and (34).

$$A_h = [(3\sqrt{3} / 2) * R_{sense}^2] \quad (33)$$
$$A_t = [(\sqrt{3} / 4) * R_{sense}^2] \quad (34)$$

Now, we need to compute the difference between one-sixth area of a circle having the radius R_{sense} and A_t , which occupies the exact 3-coverage from the corner nodes of the equilateral triangle in fig (6).

$$A1' = [(\pi\, Rsense^2 / 6) – A_t] \quad (35)$$

Therefore, one of the exact 3-coverage area within a regular hexagon from fig (6) has the area twice of the value of A1'.
Thus,

$$A2' = [2 * A1'] \quad (36)$$

Now, the total area of the exact 3-coverage and 2-coverage within the Tri-Beehive symmetric tessellation cell will be,

3-coverage: $A3' = [9 * A2'] + 6 * A_t$ (37)

2-coverage: $A4' = [A_h – (A'+ €)]$ (38)

The term '€' in equation (38) refers towards the exact 6-coverage area point for each regular hexagon (€ = zero(0) in a perfect Tri-Beehive pattern).

VI. RESULTS

In all of the three deployment patterns undertaken, a single unit cell is sufficient for the whole network coverage analysis since three of them are symmetrical in nature according to our basic assumptions. For evaluating the deployment strategies on the basis of their coverage capacity, we have assumed to have number of sensor nodes 'n' = 500 and 'R' = 150 as the radius of the circular field.

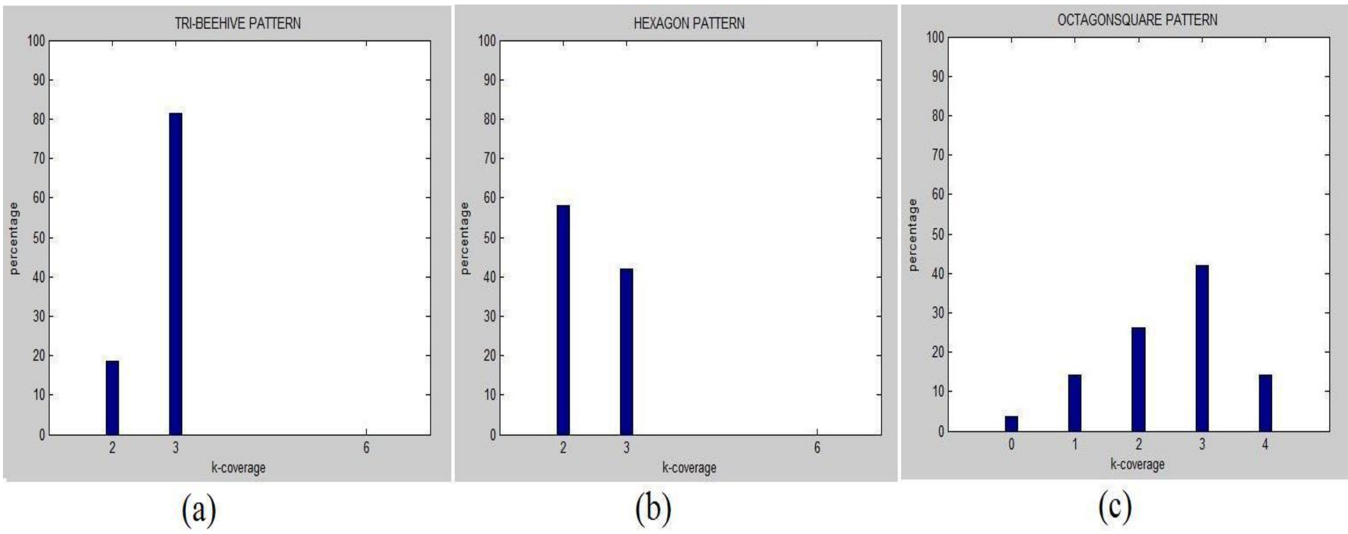


Fig (7) The K-coverage of :(a) Tri-beehive (b) Regular Hexagon (c) Octagon-Square deployments

The frequency bar graph of the exactly k-covered points of a Tri-Beehive deployment unit cell is shown in fig (7)(a) between the percentage of the coverage achieved and the value of k in k-coverage. The sensing radius , R_{sense} used for Tri-Beehive unit cell is 10 m on the basis of the equations described in 4.1. Almost two-third of the network are covered by 3-coverage whereas the rest is the exactly 2- coverage points. A negligibly small percentage of the network is 6-covered.The Tri-Beehive node deployment pattern has an average 2.81- coverage with standard deviation of 0.38.

Next is the frequency bar graph drawn for the Regular Hexagon node deployment pattern unit cell in fig (7)(b). The sensing radius, R_{sense} for regular hexagon unit cell as derived from equations formed in section 2.1 is 13m. About 60% percent of the area is within 2- coverage. The Regular Hexagon node deployment pattern has an average 2.42- coverage with standard deviation of 0.49.

The frequency bar graph between k-coverage and percentage for the Octagon-Square node deployment pattern unit cell is shown in fig (7) (c).The sensing radius, R_{sense} for octagon-square unit cell is 8m based on section 3.1. Most of the area comes under the 3- coverage. With a variation of different k-coverage, octagon-Square node deployment pattern has an average 2.49- coverage and a standard deviation of 1.02.

VII. CONCLUSION

A Wireless Sensor Network (WSN) can be composed of homogeneous or heterogeneous sensor nodes also termed as motes, which adapts the same or different coordination, sensing and computation abilities, respectively. The conclusion of this work points towards the Tri-Beehive node deployment pattern as a better option for Wireless Sensor Networks (WSN) in the sense of coverage performance evaluation, as its average coverage is better than the other two strategies.

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