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Node Deployment Strategies and Coverage Prediction in 3D Wireless Sensor Network with Scheduling

Anvesha Katti
School of Computer and System Sciences
Jawaharlal Nehru University, New Delhi, India

D.K.Lobiyal
School of Computer and System Sciences
Jawaharlal Nehru University, New Delhi, India

Abstract

Wireless sensor network (WSN) is a wireless network of spatially distributed autonomous devices using sensors to monitor physical conditions. Deployment of sensor nodes is a critical issue in WSN as it affects coverage and connectivity of the network. Coverage in wireless sensor networks is a measure of how well and for how long the sensors are able to observe the physical space. In this paper, we propose different sensor node deployment strategies for 3D WSN for maximum coverage prediction. We do a comparative study of 3D sensor node deployment strategies for coverage prediction. We also propose a scheduling algorithm to minimize the number of sensor nodes used in coverage prediction. Our study also gives a comparison between various proposed 3D sensor node deployment schemes along with the number of sensor nodes to be used in each case.

Keywords: wireless sensor networks, sensor node deployment, coverage, connectivity

I. INTRODUCTION

Wireless sensor networks (WSN), consist of spatially distributed autonomous sensors which monitor physical phenomenon and pass on the data collectively to a data collector called a sink. The WSN consist of a few to several hundred sensor nodes, which are capable of sensing in any environmental conditions. Cost constraints and detection possibility of sensor nodes have been one of the most researched areas of WSN [12]. WSNs find many applications in environmental observation and forecasting systems, habitat monitoring, intrusion detection and tracking, seismic monitoring, etc.[3]

Every sensor in a WSN has a limited sensing range and the union of the sensing ranges of all sensors reflects how well the area of sensor field is monitored known as the coverage area [4].Deployment of sensors is a major aspect influencing coverage. The deployment of a WSN affects many of its metrics such as coverage, connectivity and lifetime.

There are mainly two types of sensor node deployment: deterministic deployment and random deployment. Deterministic deployment is used where uniform sensing is needed. Random deployment is normally used in case of inaccessible terrains, disaster areas and war zones.

In random deployment, sensors are usually scattered for example air dropped [5]. Deterministic deployment is selectively deciding the locations of the sensors for uniform coverage by optimizing one or more parameters. Deterministic deployment finds applications in border surveillance, intrusion detection, and structural healthcare among others [6].

In this paper, we present a novel deterministic sensor node deployment scheme of 3D WSN consisting of prism deployment, pyramid deployment, cube deployment and hexagonal prism deployment along with finding the coverage prediction. We also propose a scheduling algorithm which will help increase the lifetime of the sensor nodes by switching off nodes and saving energy.

This paper is organized as follows: in section 2 we present the research already reported in literature, in section 3 we address various types of deployments of sensor nodes in 3D WSN and also find the coverage prediction for each of them along with the number of sensor nodes required for each type of deployment. The results are explained in section 4 and we conclude in section 5.

II. LITERATURE REVIEW

Good coverage and connectivity in WSN depends a lot on sensor node deployment. This has been an active area of research with the aim of optimizing parameters revolving around lifetime, cost, coverage and connectivity.

In [7], the authors present deployment approaches of WSNs optimizing parameters such as energy consumption and obstacle adaptability using artificial potential field and computational geometry techniques. Liu and He [8] propose an Ant Colony optimization with greedy deployment solution for maximizing coverage in grid based WSN. Authors maximize coverage while minimizing sensor movement in [9] using a complex algorithm. In the deployment algorithm introduced in [10], each node will communicate with its neighbors and tell them to move away until they are at a distance which maximizes coverage while maintaining connectivity.

III. COVERAGE PREDICTION FOR NODE DEPLOYMENTS 3D WSN ENVIRONMENT

Coverage defines monitoring environmental conditions or changes by sensors deployed in a certain region. Every sensor in a WSN has a limited sensing range and the union of the sensing ranges of all sensors is known as the network sensing coverage reflecting how well the area of sensor field is monitored. One of the major factors affecting coverage is an effective deployment strategy. Coverage measures how well each point in the sensing field is covered by sensors. A sensor network deployment can usually be classified as either a regular deployment or random deployment as described earlier. We develop a deployment strategy for regular placement of sensor nodes and assume the sensor nodes are static, i.e. they stay in the same place once they are deployed. As compared to random deployment, regular deployment of sensors in WSNs provide better sensing coverage and a higher degree of connectivity. Good deployment helps us to place the nodes in a manner to maximize coverage. Coverage prediction for a sensor node is the ratio of the volume covered by the node to the whole volume of deployment. [11]

We derive the coverage prediction for different deployment strategies such as a prism, pyramid, cube, and hexagonal prism type of deployment and also find the number of sensors used in each case for coverage prediction. We also give a comparison of the different deployment strategies with the number of sensor nodes. We start by describing the disk sensing model which is one of the most widely used models.

A. *Coverage using Disk Sensing Model*

The sensor has a constant sensing range r with volume $a = \pi r^3$. If a target node lies in the sensing range of a sensor it is said to be covered. Probability of target detection is defined as the ratio of sensing volume to network volume expressed as P_d=v/V where V is network volume and N is the number of sensor nodes deployed uniformly. The probability of target detection P_c by at least one of the N sensors can be expressed as

$$P_c = 1 - (1 - P_d)^N \qquad (1)$$

By applying the equality approximation $[1-x]^n \approx e^{-nx}$ as n is very large, the stated equation can be rewritten as

$$P_c = 1 - exp\left(\frac{-N\pi r^2}{A}\right). \qquad (2)$$

This model is generally used in comparison with different probabilistic sensing models[12].

B. *Prism Sensor Node Deployment Strategy*

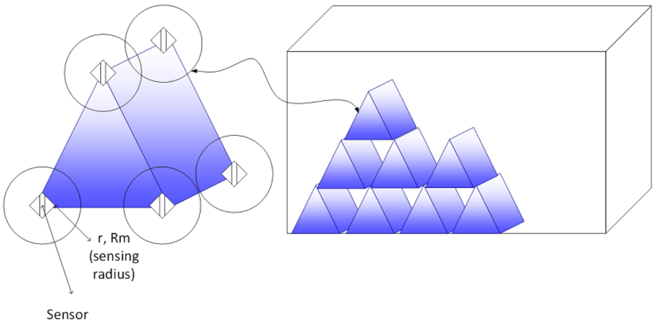

Fig.1 Prism type sensor node deployment

We take a cube sensing field of side a with the cube being divided into small equilateral prism regions. Assumptions include sensors at the end points of the prism. Sensing radius is the radius of the sphere at the end points of the sensor node (r) and varies between 0 and R_{max} with R_{max} being the maximum radius and 0 being the minimum. It is assumed that the sensors placed at the endpoints have equal sensing range depicted by the radius of the sphere. Coverage Prediction is the ratio of the sensing volume to total volume. For prism sensor deployment this is expressed as

$$C_f = \frac{2\pi r^3}{3\sqrt{3}R_{max}{}^3} \qquad (3)$$

C. Cube Node Deployment

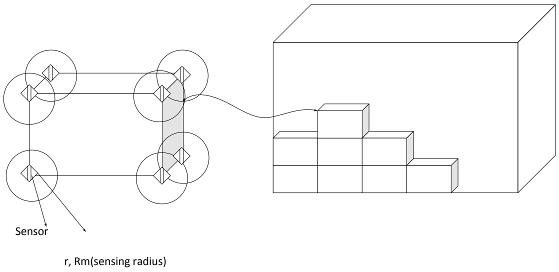

Fig.2. Cube type sensor node deployment

In fig.2 we take a cube sensing field of side a with the cube being divided into small equilateral cube regions. Assumptions include sensors at the end points of the cube. Sensing radius is the radius of the sphere at the end points of the sensor node (r) and varies between 0 and R_{max} with R_{max} being the maximum radius and 0 being the minimum. It is assumed that the sensors placed at the endpoints have equal sensing range depicted by the radius of the sphere. Coverage Prediction is the ratio of the sensing volume to total volume. For cube sensor deployment this is expressed as

$$C_f = \frac{\pi r^3}{3 R_{max}{}^3} \qquad (4)$$

C. *Hexagonal Prism Node Deployment*

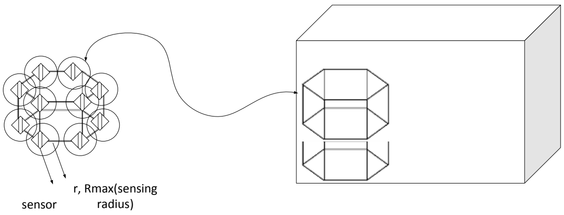

Fig.3. Hexagonal Prism Node Deployment

In fig.3 we take a cube sensing field of side a with the cube being divided into small equilateral hexagonal prism regions. Assumptions include sensors at the end points of the hexagonal prism. Sensing radius is the radius of the sphere at the end points of the sensor node (r) and varies between 0 and R_{max} with R_{max} being the maximum radius and 0 being the minimum. It is assumed that the sensors placed at the endpoints have equal sensing range depicted by the radius of the sphere. Coverage Prediction is defined as the ratio of the sensing volume to total volume. For hexagonal prism sensor deployment, this is expressed as

$$C_f = \frac{4\pi r^3}{9\sqrt{3} R_{max}{}^3} \qquad (5)$$

E. Pyramid Node Deployment

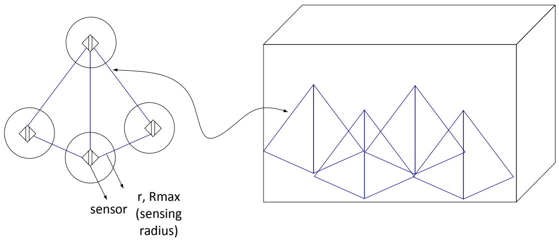

Fig.4. Pyramid Node Deployment

In fig.4 we take a cube sensing field of side a with the cube being divided into small equilateral pyramid regions. Assumptions include sensors at the end points of the pyramid. Sensing radius is the radius of the sphere at the end points of the sensor node (r) and varies between 0 and R_{max} with R_{max} being the maximum radius and 0 being the minimum. It is assumed that the sensors placed at the endpoints have equal sensing range depicted by the radius of the sphere. Coverage Prediction is the ratio of the sensing volume to total volume. For pyramid sensor deployment this is expressed as

$$C_f = \frac{5\pi r^3}{12 {R_{max}}^3} \tag{6}$$

F. Sensor Node Estimation

By putting $r=R_{max}$ in (3), (4), (5) and (6) the maximum coverage prediction for prism is 2π/3√3, the maximum coverage prediction for cube is π/3, the maximum coverage prediction for hexagonal prism is 4π/9√3, the maximum coverage prediction for pyramid is 5π/12. We can approximate the number of sensor nodes to cover the sensing field using Prism deployment as

$$N_s(Prism) = \frac{2a^3}{3\sqrt{3} {R_{max}}^3} \tag{7}$$

Number of sensor nodes to cover the sensing field using Cube deployment as

$$N_s(Cube) = \frac{a^3}{3 {R_{max}}^3} \tag{8}$$

Number of sensor nodes to cover the sensing field using Hexagonal Prism deployment as

$$N_s(Hexagonal\ Prism) = \frac{4a^3}{9\sqrt{3} {R_{max}}^3} \tag{9}$$

Number of sensor nodes to cover the sensing field using Pyramid deployment as

$$N_s(Pyramid) = \frac{5a^3}{12 {R_{max}}^3} \tag{10}$$

IV. ENERGY PRESERVING SCHEDULING PROTOCOL

We present a scheduling algorithm which helps us to extend the lifetime of the sensor nodes with maintaining sufficient coverage. Sensors with overlapping coverage areas of more than fifty percent are turned off to save energy and are woken up at the appropriate time to extend the network lifetime. Each sensor implements the algorithm independently. The sensor can be in any of the four states: Active, Sleep, Idle and Dead. Each active sensor will try to enter the sleep mode from where after a specific time interval it goes back to the active mode again. The sensor node can also enter the idle mode from the active mode after which it enters the dead mode where it is terminated if it has low energy. The node wishing to enter the sleep mode, first checks the neighbors whose overlap of sensing area is greater than fifty percent and broadcasts a sleeping request (SR) message to all neighbors. If all the neighbors agree the node can enter the sleep mode. If any of the neighbor rejects, the node keeps the trial active and attempts again after a predefined time. The neighboring node which receives this request (SR) recalculates the coverage ignoring the requesting sensor. If the coverage is sufficient then a positive acknowledgment (PAK) is given else a negative acknowledgment (NAK) is given. Multiple sensors can move to the sleep mode simultaneously provides an advantage to our algorithm. It is necessary that only one sensor within the neighborhood is allowed to send a request at a time. Neighbour nodes randomly contend with each other to avoid collisions. We assume the sensor nodes whose sensing range overlaps with each other can communicate directly [13]. We also assume the sensor node knows the location of the neighboring sensor nodes. Figure 5 shows the state transition diagram of the algorithm.

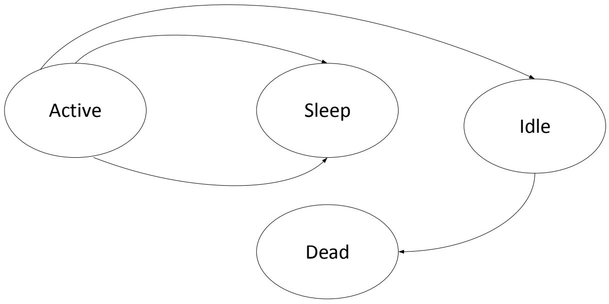

Fig.5. State transition diagram for scheduling algorithm

In the following, we explain how the sensor node works.

i. Active- Initially the sensor node s_i stays in the active state to sense the environment and check the neighbor sensor node overlap. It broadcasts the request to sleep message (SR) to all the neighbors and waits for the reply for a predetermined time using a timer T1. Each of the neighbors s_j's recalculate the coverage by ignoring the s_i. If the coverage is sufficient without s_i a positive acknowledgment (PAK) is sent else a negative acknowledgment (NAK) is sent. The three results that can be received for s_i request are:

1. All the neighbors send a positive acknowledgment (PAK) the node s_i goes to sleep state.
2. If any negative acknowledgment (NAK) is received s_i stays in the active mode.
3. If the timer goes off before all the replies from the neighbors are received, s_i stays in the active mode.

ii. Sleep – The node s_i broadcasts a confirm message(CON) to indicate to all neighbors that it is going to the sleep mode and should not be taken into account. It remains in the sleep state until it is woken by the neighbor sensor nodes.

iii. Idle: The sensor node in the active mode can go to the idle mode when the energy goes below a threshold level. It starts a timer T2 and sends an *Urgent* message to all the neighbor nodes that it is going to die soon and the sleeping neighbor sensor nodes should be woken up to take over. The active neighbor sensor nodes which have a list of the sleeping nodes with overlapping coverage send a message to them to get to the active mode immediately.

iv. Dead/Terminated: The sensor node runs out of energy and terminates.

V. RESULTS AND ANALYSIS

We consolidate our results in this section. We have used Matlab for our simulations. The simulations show the Coverage Prediction and the Number of Sensors for different kinds of sensor node deployment. The entire sensing field is assumed to be a cube with volume V = 500*500*500 m^3. The maximum sensing radius R_{max} is assumed to be 20 m. The sensing field is partitioned into small equilateral prism, cube, and hexagonal prism, sub-regions of side 20 m.

The graph in figure 6 shows the sensing radius and coverage prediction for the various deployments strategies of cube, prism, hexagonal prism, pyramid and random deployment. We observe that the pyramid type of deployment gives us the maximum coverage and the hexagonal prism gives the least coverage prediction amongst all the various types of deployment strategies. The Prism deployment strategy also reaches very close to maximum coverage prediction of pyramid deployment. Random deployment as can be seen gives a very random picture of the coverage prediction.

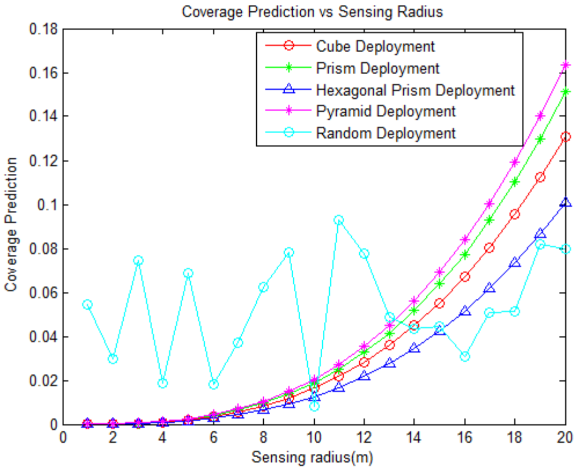

Fig.6 Coverage Prediction vs Sensing radius

Figure 7 represents the sensing radius with the number of sensor nodes required in each of the deployment strategies of cube, prism, hexagonal prism, pyramid and random deployment. We can see that the maximum number of sensor nodes are required by the pyramid deployment followed by prism deployment, cube deployment and hexagonal prism deployment. Therefore, the pyramid and prism type of deployment provide good coverage prediction with almost same number of sensors.

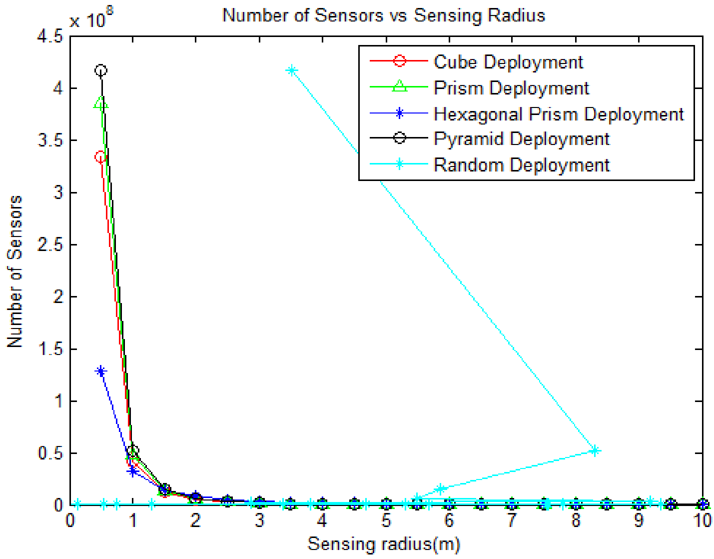

Fig.7. Number of sensors vs sensing radius

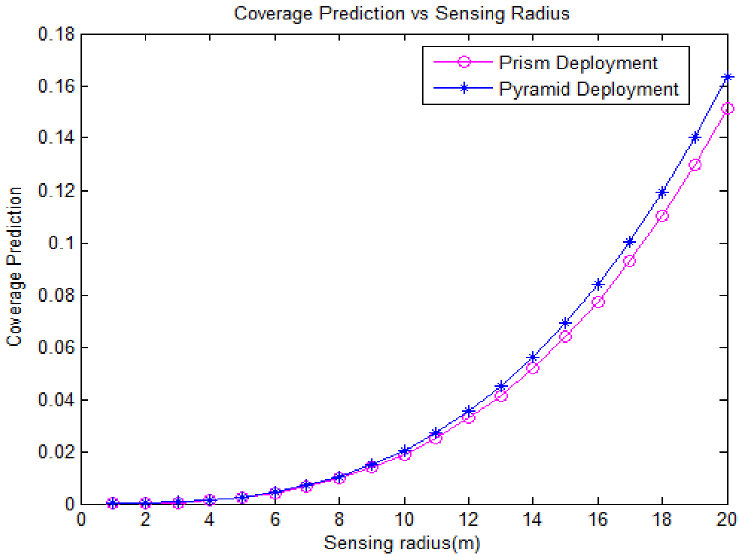

Fig.8. Coverage prediction vs sensing radius

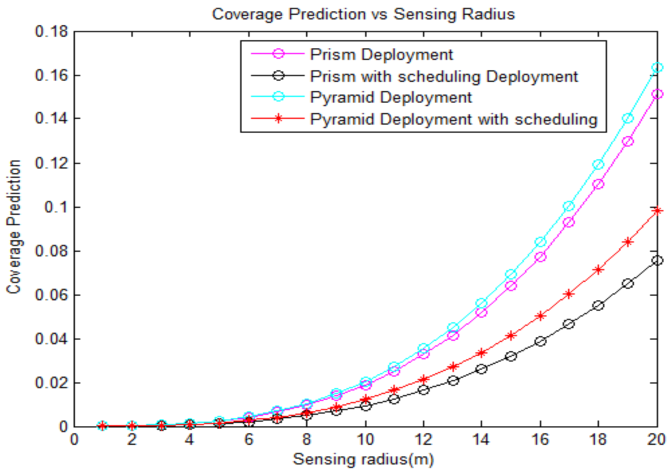

Fig.9. Coverage prediction vs sensing radius

The above figure 8 represents the coverage prediction for prism and pyramid deployment since both have the maximum nearly equal coverage prediction. While coverage prediction for the pyramid deployment comes to around 0.16, prism comes a close second with 0.15.

The above figure 9 represents the coverage prediction with scheduling. We observe that with scheduling the coverage in pyramid deployment comes down to about 0.10 from 0.16 and prism deployment comes down further to about 0.08. The difference with scheduling pyramid deployment in coverage prediction is about 0.06 but considering the saving of energy that we are having in terms of the number of nodes it is huge.

The graph in figure 10 depicts the coverage prediction for cube deployment with and without scheduling. We observe the coverage prediction drops down significantly when we use scheduling in cube deployment.

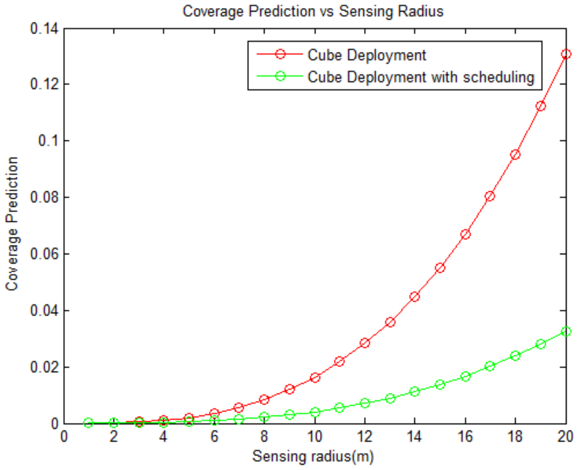

Fig.10.Coverage prediction vs sensing radius

The graph in figure 11 depicts the number of sensor nodes required for prism and pyramid deployment with scheduling. We can clearly see that pyramid deployment uses the highest number of nodes whereas using scheduling the number of sensor nodes drops down signficantly to more than half. The number of sensor nodes required for prism deployment is a tad bit lower than pyramid deployment which comes down further with scheduling. We interpret that although the deployment of pyramid and prism is the best which gives us maximum coverage with least number of nodes if used with scheduling.

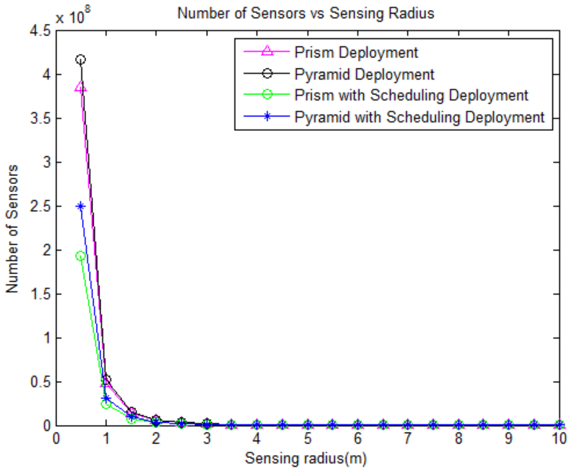

Fig.11.Coverage prediction vs number of sensors

The graph in figure 12 shows the coverage prediction for hexagonal prism deployment with and without scheduling. We observe the coverage prediction drops down significantly when we use scheduling in hexagonal prism deployment.

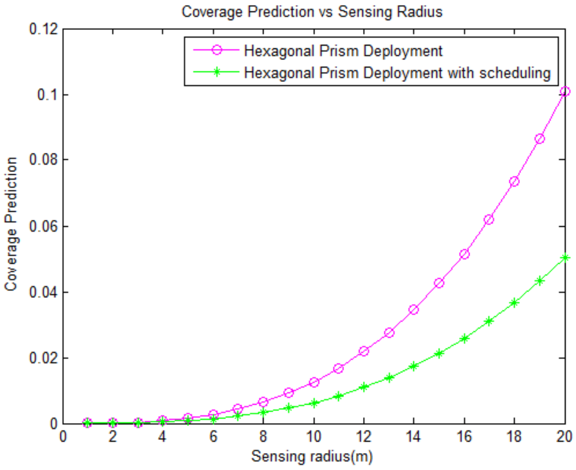

Fig.12.Coverage prediction vs number of sensors

VI. CONCLUSION

We have presented the different types of sensor node deployment schemes for 3 D wireless sensor networks for finding the coverage prediction. Various kinds of deployment of sensor nodes help to understand the major role deployment plays in the coverage of wireless sensor networks. We present the prism, cube, pyramid and hexagonal prism type of node placement. We also give a comparative review of the various node deployment schemes discussed with the coverage prediction and the number of sensors used in each case. We also present a scheduling algorithm for the above discussed schemes and find the difference in coverage prediction and number of sensor nodes required for each case. We find that pyramid node deployment scheme has the highest coverage prediction which is almost equal to prism type of deployment and hexagonal prism has the least coverage prediction. Also although the pyramid deployment has the best coverage prediction but it also uses the maximum number of sensors while the hexagon prism uses the least number of sensors along with the lowest coverage prediction. When we use the pyramid type of deployment with scheduling we get a very good coverage prediction using less number of sensors. Therefore most practical deployment scheme is either the pyramid deployment with scheduling or the prism deployment with scheduling which uses an average number of sensors for good coverage prediction.

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