Sensing and Communication Energy Consumption in Static Sensor Network

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ABSTRACT
A sensor network normally constitutes a Wireless ad-hoc network, meaning that in it each sensor supports a multi-hop routing algorithm (several nodes may forward data packets to the base station). But the sensor nodes suffer from constrained resources i.e., sensors have limited energy resources and their functionality continue only until their energy is drained out. Therefore the limited energy resource in these nodes demands an efficient consumption of these resources which should be managed wisely to extend the lifetime of sensors. In this paper, we study the problem of energy-efficient coverage and we propose various models for placing nodes in a static network. We consider a hexagonal model in two-dimensional deployment and a cubical/hexagonal-prism model for deploying sensors in space. Further, we have considered a rectangular grid divided into regular hexagons and the space covered by cubes and hexagonal-prisms. We have calculated the sensing energy and communication energy consumptions in each model and compared the same with the existing models. However, as far as we know there is no such model for covering the space.

General Terms
Sensing energy efficiency, Communication energy efficiency, Coverage et. al..

Keywords
energy-consumption, hexagonal-prism, cube, coverage models, sensing nodes.

1. INTRODUCTION
Wireless Sensor Networks are a new class of distributed systems that are an integral part of the physical space they inhibit [1]. A sensor network is an infrastructure comprised of sensing (measuring), computing, and communicating elements that give the ability to observe, and react to events and phenomena in specified environment. It is a fast growing and exciting research area that has attracted considerable attention in the recent past. With its origin in the early nineties, the subject of wireless sensor networks has seen an explosive growth in interest in both academia and industry [5].Unlike most computers which work primarily with data created by humans, sensor networks reason about the state of the worlds that embodies them [8]. Wireless sensor networks are providing tremendous benefit for a number of industries. The ability to add remote sensing points, without the cost of running wires, results in numerous benefits including energy and material savings, process improvements, labor savings, and productivity increases. Today Wireless Sensors Networks are being widely deployed.

A sensor network consists of multiple detection stations called sensor nodes, each of which is small, lightweight and portable. Every sensor node is equipped with a transducer, microcomputer, transceiver and power source. The transducer generates electrical signals based on sensed physical effects and phenomena. The microcomputer processes and stores the sensor output. The transceiver, which can be hard-wired or wireless, receives commands from a central computer and transmits data to that computer. The sensor nodes consume power for sensing, communicating and data processing. This power is derived from the electric utility or from a battery [4]. A sensor node might vary in size from that of a shoebox down to the size of a grain of dust. The cost of sensor nodes is similarly variable, ranging from hundreds of dollars to a few pennies, depending on the complexity of the individual sensor nodes [2]**.** As wireless sensor nodes are typical electronic devises, they can be equipped with a limited power source of less than 0.5-2 ampere-hour and 1.2-3.7 volts. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and communications bandwidth [2].

Energy is a primary constraint in the design of sensor networks. This fundamental energy constraint further limits everything from data sensing rates and link bandwidth, to node size and weight. Large volumes of sensor data generated will make the data transmission within the network to a single information sink with minimal latency and energy is a very challenging task [6]. This means, energy consumption is one of the most important performance metrics for wireless ad hoc sensor networks because it directly relates to the operational lifetime of the network [3]. As, ssensors have limited energy resources and their functionality continues until their energy drains, therefore, energy resources for sensor networks should be managed wisely to extend the lifetime of sensors [7]. A sensor node should be small in size, consume extremely low energy, operate in high volumetric densities, be autonomous and operate unattended, and be adaptive to the environment

In this paper, we have estimated energy efficiency in two-dimensional and three-dimensional regions considering coverage by sensors of two different sensing ranges (i.e. Heterogeneous sensors). The region of interest is divided into regular hexagons in case of a plane region and the region of interest in space is divided into cubes. We have also considered a region consisting of a single hexagonal-prism. The sensor nodes are deployed on the vertices of these configurations. The sensing range of neighboring nodes are considered tangential to each other. To cover the uncovered area/region of these configurations we have deployed an additional sensor at the center of the configuration. This extra sensor has an adjustable sensing range. By adjustable sensing range we mean that the sensing range of the extra sensor is determined according to the gap to be covered by the extra sensor, which has not been covered by the sensors at the vertices.

Network Connectivity (for communication among sensors) is ensured by assuming that all the active sensor nodes form a minimum spanning tree (MST) and each sensor node adjusts its communication range to reach its farthest neighbor on the tree. As we know that the amount of energy consumed for communication by sensors depends upon the distance between the communicating sensors, therefore for the hexagon we assume that the energy consumed for communication by a sensor is proportional to the square of the distance from itself to its farthest neighbor on the tree by a factor of β (power consumption per unit). For the cube and Hexagonal-Prism, energy consumed for communication by a sensor is proportional to cube of the distance from itself to its farthest neighbor on the tree by a factor of δ (power consumption per unit time). The model with the least sensing and communication energy consumption is considered to be the best in terms of sensing and communication energy efficiency respectively. We have considered the energy-efficiency of sensor network for these models. In the two-dimensional region we provide coverage using hexagons as tiles in the rectangular area and in the three-dimensional space coverage is provided using cubes.

The remaining of the paper is organized as follows. Section 2 describes the Proposed Coverage Models, and provides an estimate of the sensing energy and communication energy consumption for these models. Section 3 provides an analysis of the energy consumptions for various models and Section 4 concludes the paper.

2. PROPOSED COVERAGE MODELS

In the two-dimensional area we consider a unit as a regular hexagon. Sensor nodes of two different strengths are used for deployment. Six nodes of equal strength are placed at the six vertices of the hexagon. The sensing radius is considered as half of the length of a side of hexagon. Still some area of the hexagon remains uncovered. For this another node of higher strength is placed at the center of the hexagon. . These nodes are placed in such a manner so that there is minimum overlapping. For deployment in space we consider two different types of regular solids, (i) a cube and (ii) a hexagonal-prism. Nodes of lower strength are placed at the vertices and a node of higher strength is placed at the center of the cube/hexagonal-prism. The side of a cube/hexagonal-prism is taken as twice the sensing range of the weaker node.

Next, we consider a rectangular region and divide it into regular hexagons. In case of rectangular parallelepiped, space is filled with regular cubes, and the nodes are deployed in a similar way, as in the case of unit models, cube/hexagonal-prism. We evaluate the sensing energy consumption and communication energy consumption for individual unit models and also for a two-dimensional area and a three-dimensional space. Larger is the area/space smaller is the per unit energy consumption (sensing and communication energy consumption) The detailed descriptions of sensing and communication energy consumption are included in the next section.

3. SENSING ENERGY AND COMMUNICATION ENERGY CONSUMPTION

In this section, we consider and calculate the sensing energy and communication energy consumptions for different units (hexagonal-prism, cube, hexagon), and also for rectangular area and rectangular parallelepiped in space.

3.1 Hexagonal-Prism

(i) Sensing Energy Consumption

In the hexagonal-prism 12 sensing nodes are deployed at the 12 vertices, such that the sensing ranges of neighboring nodes are tangential. The height of the hexagonal-prism is taken equal to the length of the side of the regular hexagonal face and all vertical faces are squares of side equal to the side of hexagonal-face. The sensing radius of the nodes at the vertices is R, which is half of the length of the side of the hexagonal-face. The node placed at the center of the hexagonal-prism has sensing radius 2R.

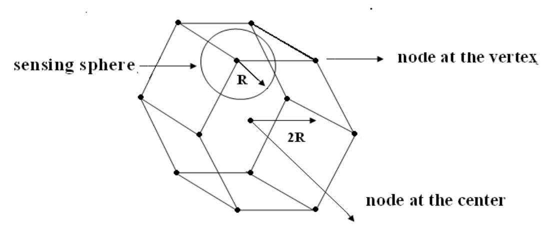

Figure 1: Hexagonal-Prism

In Fig.1 we can see that the node at the vertex forms a sensing sphere. Similarly all other nodes deployed at the vertices and at the center of the hexagonal-prism forms sensing spheres.

Since the sensing range of a node is R, each sensing node will cover a spherical volume $4\pi R^3/3$, which we call a sensing sphere for sensing. A part of this space will be inside the prism and the remaining will be outside the prism. We define the Coverage Density (CD), as the ratio of the total volume of the portions of the sensing region inside the hexagonal-prism (TV), divided by the volume of the hexagonal-prism (VM). Smaller the value of CD, better the energy-efficiency.

The total volume of the portions of the sensing spheres inside the hexagonal prism, the volume of the hexagonal-prism and the Coverage Density of the hexagonal prism respectively are:

$$TV = \frac{8}{3}\pi R^3 + \frac{32}{3}\pi R^3 = 40\pi R^3/3,$$

$$VM = 12\sqrt{3} R^3$$

$$CD = TV/VM = 40\pi R^3/36\sqrt{3}R^3 = 2.014311$$

Therefore, the sensing energy consumption of the sensors deployed in the hexagonal-prism is:

$$SC_{hexagonal-prism} = TV.\alpha = 40\pi R^3.\alpha/3$$

and, Sensing Energy Consumption per Unit Volume is:

$$SEV_{hexagonal-prism} = SC_{hexagonal-prism}/VM$$
$$= 40\pi R^3.\alpha/36\sqrt{3}R^3 = 2.014311\alpha$$

where α is the power consumption per unit time.

(ii) Communication Energy Consumption

The minimum distance between any two adjacent sensing-nodes in the hexagonal-prism configuration is $d_{hexagonal-prism} = 2R$ .The consumption of energy in sensing by a sensing node is proportional to the sensing region inside the prism. The total sensing region ($P_{hexagonal-prism}$) of all the 12 sensors at vertices and 1 sensor at the center is equivalent to sensing by $(2+1) = 3$ sensors. Therefore, the Communication Energy Consumption (CC) and the Communication Energy Consumption per Unit Volume (CEV) for sensors deployed in the hexagonal-prism is:

$$CC_{hexagonal-prism} = P_{hexagonal-prism}.\delta.d^3_{hexagonal-prism}$$
$$= (3).\delta.(2R)^3$$

$$CEV_{hexagonal-prism} = CC_{hexagonal-prism}/VM =$$
$$(3).\delta.(2R)^3/12\sqrt{3}R^3 = 1.154701\delta$$

where δ is the power consumption per unit.

3.2 Cube

(i) Sensing Energy Consumption

In case of a cube, eight sensing-nodes are deployed at the eight vertices. The sensing radius of the nodes at the vertices is R, which is half of the length of the side of the cube, and the radius of the sensing node placed at the center of the cube is $\sqrt{2}R$. Since the sensing range of a node is R, each sensing node will cover a spherical volume $4\pi R^3/3$, which we call a sensing sphere for sensing. A part of this space will be inside the cube and the remaining will be outside the cube.

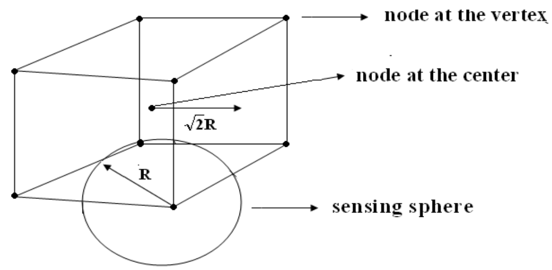

Figure 2: Cube

In Figure- 2 we can see that the node at the vertex forms a sensing sphere. Similarly all other nodes deployed at the vertices and at the center of the cube forms a sensing sphere.

The total volume of the portions of the sensing spheres inside the cube (TV), the volume of the cube (VM) and the Coverage Density (CD) respectively are:

$$TV = \frac{4}{3}\pi R^3 + \frac{8\sqrt{2}}{3}\pi R^3 = (4+8\sqrt{2})\pi R^3/3,$$

$$VM = 8R^3$$

$$CD = TV/VM = (4+8\sqrt{2})\pi R^3/24R^3$$
$$= 2.003544$$

So, the sensing energy consumption of sensors placed in the cube is:

$$SC_{cube} = TV.\alpha = (4+8\sqrt{2})\pi R^3.\alpha/3.$$

and, Sensing Energy Consumption per Unit Volume is:

$$SEV_{cube} = SC_{cube}/VM =$$
$$(4+8\sqrt{2})\pi R^3.\alpha/24R^3 = 2.003544.\alpha$$

where α is the power consumption per unit.

For the deployment of cubes in space we consider a rectangular parallelepiped of length 'L', breadth 'B' and height 'H', which is divided into cubes of sides of length 2R. Sensors placed at the vertices of the cubes have uniform sensing range R, which is half of the length of the side of the cube. The sensing range of the sensor placed at the center of the cubes is $\sqrt{2}R$. The entire space(volume) is covered by m*n*p cubes, where

$L = n*2R$, $B = m*2R$ and $H = p*2R$.

The number of cubes in a row are numbered 1 to p. number of columns are numbered 1 to n, and number of cubes along the height of the rectangular parallelepiped are numbered 1 to m.

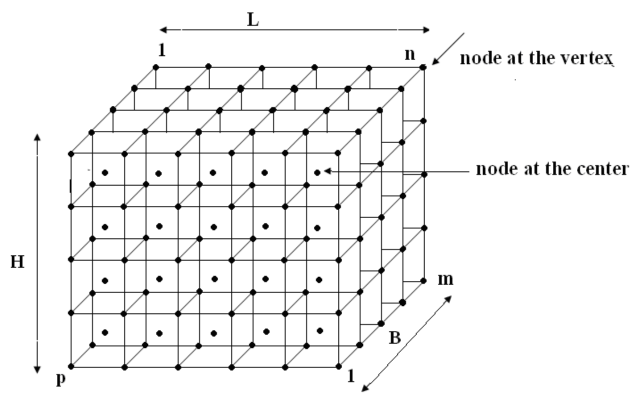

Figure 3: rectangular parallelepiped divided into cubes

The sensing energy consumptions for varying volumes are given in table 1:

Table 1. SEV when rectangular parallelepiped is divided into cubes

Values of m, n, p			Volume of parallelepiped (cubit units)	Volume of sensing spheres in parallelepiped	SEV
m	n	p			
3	4	4	196608	355328.3661	1.807293529 α
4	4	5	327680	579352.5035	1.768043529 α
4	5	6	491520	856167.3152	1.741876862 α
5	6	7	860160	1466139.202	1.70449591 α
6	6	7	1032192	1746505.602	1.692035592 α

(ii) Communication Energy Consumption

The minimum distance between any two adjacent nodes in the cube is $d_{cube} = \sqrt{3}R$. The consumption of energy in sensing by a sensing node is proportional to the sensing region inside the cube. The total sensing region (P_{cube}) of all the 8 sensors at vertices and 1 sensor at the center is equivalent to sensing by $(1+1) = 2$ sensors.

Therefore, the Communication Energy Consumption (CC) and the Communication Energy Consumption per Unit Volume (CEV) for the sensors placed on the cube is:

$$CC_{cube} = P_{cube}.\delta.d^{3}{}_{cube} = (2).\delta.(\sqrt{3}R)^{3}$$

$$CEV_{cube} = CC_{cube}/VM$$
$$= (2).\delta.(\sqrt{3}R)^{3}/8R^{3} = 1.299038\delta$$

The corresponding communication energy consumptions by filling space with cubes for varying volumes are given in table 2:

Table 2. CEV when rectangular parallel pied is divided into cubes

Values of m, n, p			Volume of parallel epiped (cubit units)	Volume of sensing spheres in parallelepiped	CEV
m	n	p			
3	4	4	196608	355328.3661	1.055468461 δ
4	4	5	327680	579352.5035	1.006754532 δ
4	5	6	491520	856167.3152	0.974278579 δ
5	6	7	860160	1466139.20	0.927884361 δ
6	6	7	1032192	1746505.602	0.912419622 δ

Fig. 4 below gives a graphical representation of the different values of sensing energy and communication energy consumptions per unit volume for the varying volumes when cubes are deployed in a rectangular parallelepiped.

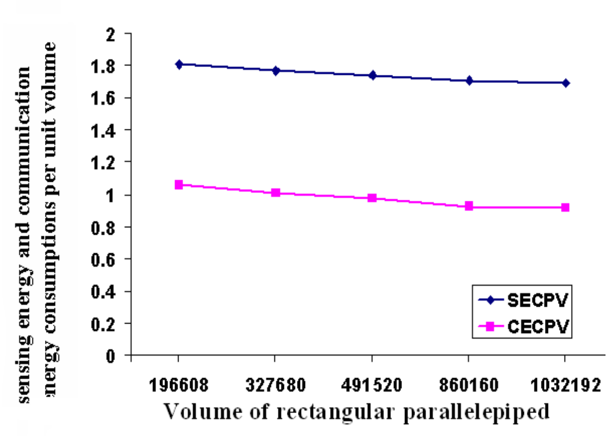

Figure 4: sensing and communication energy consumptions per unit volume for varying sizes of rectangular parallelepiped filled by cubes

To obtain the sensing energy and communication energy consumptions, the sensing range of the nodes at the vertices is taken as fixed, R=8m.The length (L), breadth (B) and height (H) are varied.

3.2 Hexagon

(i) Sensing Energy Consumption

In case of a hexagon there are six equal sensing nodes deployed at the six vertices of the hexagon, having sensing radius R, which is half of the length of the side of the hexagon, and the sensing range of the node placed at the center of the hexagon is a sensing disk of radius $\sqrt{3}R$ Since the sensing range of a node is R, each sensing node will cover a circular area πR^2, which we call a sensing disk for sensing. A part of this space will be inside the hexagon and remaining will be outside the hexagon.

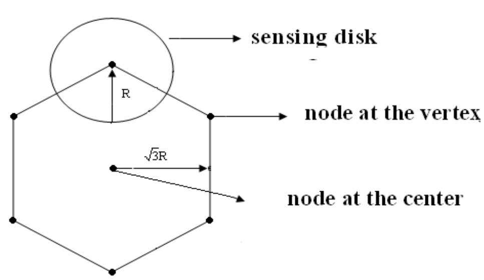

Figure 5: Hexagon

In Figure 5 we can see that the node at the vertex forms a sensing disk. Similarly all other nodes deployed at the vertices and at the center of the hexagon forms sensing disks.

The total area of the portions of the disks inside the hexagon (TA), area of the hexagon (AM), and the Coverage Density (CD) respectively are:

$$TA = 2\pi R^2 + 3\pi R^2 = 5\pi R^2,\ AM = 6\sqrt{3}R^2$$

$$CD = TA/VM = 5\pi R^2/6\sqrt{3}R^2 = 1.510733$$

We suppose that the sensing energy consumption is proportional to the area of the sensing disk by a factor of λ, or the power consumption per unit. Then, sensing energy consumption for the hexagon is:

$$SC_{hexagon} = TA.\alpha = 5\pi R^2.\lambda$$

and Sensing Energy Consumption per unit area is:

$$SEA_{hexagon} = SC_{hexagon}/AM$$
$$= 5\pi R^2.\lambda\sqrt{3}R^2 = 1.510733.\lambda$$

Now, we consider these parameters for a rectangular region in a plane that is a two-dimensional region. For this purpose we divide the whole region into regular hexagonal tiles. We consider a rectangular field of length ‘L’ and breadth ‘B’ which is divided into regular hexagons of sides of length 2R. The sensors at the vertices of the hexagons have uniform sensing range R, which is half of the length of the side of the hexagon, and the sensing range of all the sensors placed at the center of the hexagons is $\sqrt{3}R$. The whole rectangular area is covered by $m * n$ hexagons, where

$$L = (n-1) * 2R\sqrt{3}$$

and $B = (2m-1) * 2R$.

However, the hexagons covering the boundary of the rectangle also cover some extra area. Nodes are not deployed on those vertices of these hexagons which are outside the rectangular region. Portions of sensing area of some of the nodes, deployed on the boundary of the rectangular area, lying outside the rectangular region is ignored, that is not included in sensing area.

The sketch of the model is given in Figure 6, where black dots presents the position of nodes

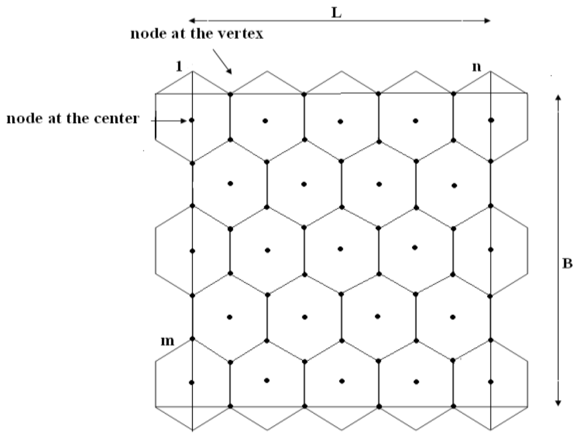

Figure 6: Hexagons deployed in a rectangular grid

The sensing energy consumptions for the varying rectangular areas are given in table 3:

Table 3. SEA when a rectangular grid is divided into regular hexagons

Values of m, n		Area of rectangular grid (square units)	Area of sensing disk	SEA
m	n			
2	2	65180.53599	83398.4	1.27949853 λ
3	3	218598.6683	264262.4	1.208893 λ
4	4	508585.5427	601875.2	1.183429629 λ
5	5	977708.0399	1144467.2	1.170561306 λ
6	6	1668533.04	1940268.8	1.162859082 λ

(ii) Communication Energy Consumption

The minimum distance between any two adjacent sensing-nodes in the hexagonal configuration is $d_{hexagon}$ = 2R.The part of the sensor's communication energy used inside the hexagon is $P_{hexahon}$ = (2+1) =3.

Therefore, The Communication Energy Consumption (CC) and the Communication Energy Consumption per Unit Area (CEA) for the hexagon are:

$$CC_{hexagon} = P_{hexahon}.\beta . d^2_{hexagon} = (3).\ \beta\ .\ (2R)^2$$

$$CEA_{hexagon} = CC_{hexagon}/AM$$
$$= (3).\beta . (2R)^2 / 6\sqrt{3}\, R^2 = 1.154701\beta$$

where β is the power consumption per unit.

The communication energy consumptions for the varying rectangular areas are given in table 4:

Table 4. CEA when rectangular grid is divided into regular hexagons

Values of m, n		Area of rectangular grid (square units)	Area of sensing disk	CEA
m	n			
2	2	65180.53599	83398.4	0.977961 β
3	3	218598.6683	264262.4	0.923995 β
4	4	508585.5427	601875.2	0.904532 β
5	5	977708.0399	1144467.2	0.894697 β
6	6	1668533.04	1940268.8	0.888809 β

Fig. 7 below gives a graphical representation of the sensing energy and communication energy consumptions per unit area for varying area when a rectangular grid is divided into hexagonal tiles and nodes are placed in a manner already described.

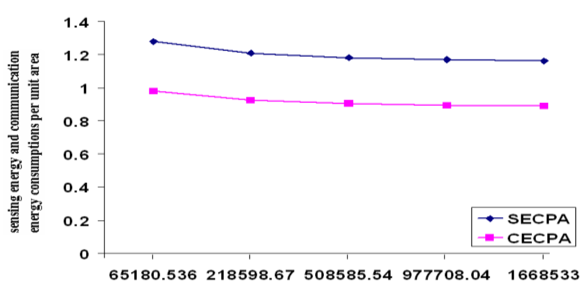

Figure 7: sensing and communication energy consumptions per unit area

To obtain the sensing energy and communication energy consumptions, the sensing range of the nodes at the vertices is kept at a fixed value of R=8m.The length (L), and breadth (B) are varied.

4. ANALYSIS OF THE PROPOSED MODELS

A summary of the results for the sensing and communication energy consumption for the hexagon, cube and hexagonal-prism as unit models, and the hexagon and cube when deployed in two-dimensional area and three-dimensional space respectively are given in Table 5:

Table 5 . sensing and communication energy consumptions per unit area/volume for hexagon, cube, hexagonal-prism as unit models

	Hexagon	Cube	Hexagonal Prism
SEA/SEV	1.512 λ	2.004 α	2.014 α
CEA/CEV	1.155 β	1.299 δ	1.155 δ

We can see here that Hexagon is best in terms of sensing energy and communication energy consumption per unit area/volume.However, communication energy efficiency remains unchanged in a hexagonal tile and hexagonal-prism.Therefore, we can say that hexagonal model is best among other models for the overall energy-effeciency (sensing and communication energy efficiency)

sensing and communication energy consumptions when a rectangular area is divided into regular hexagons are given in table 6

Table 6. SEA and CEA when rectangular grid is divided into rectangular hexagons.

Values of m, n		Area of rectangular grid (square units)	Area of sensing disk	SEA	CEA
m	**n**				
2	2	65180.53599	83398.4	1.27949853 λ	0.977961 β
3	3	218598.6683	264262.4	1.208893 λ	0.923995 β
4	4	508585.5427	601875.2	1.183429629 λ	0.904532 β
5	5	977708.0399	1144467.2	1.170561306 λ	0.894697 β
6	6	1668533.04	1940268.8	1.162859082 λ	0.888809 β

sensing and communication energy consumptions when space is filled by cubes is given in table 7.

Values of m, n, p			Volume of parallel-epiped (cubit units)	Volume of sensing spheres in parallelepiped	SEV	CEV
m	**n**	**p**				
3	4	4	196608	355328.3661	1.807293529 α	1.055468461 δ
4	4	5	327680	579352.5035	1.768043529 α	1.006754532 δ
4	5	6	491520	856167.3152	1.741876862 α	0.974278579 δ
5	6	7	860160	1466139.202	1.70449591 α	0.927884361 δ
6	6	7	1032192	1746505.602	1.692035592 α	0.912419622 δ

Table 7. SEV and CEV when rectangular parallelepiped is filled with cubes

We can see that the sensing/communication energy consumption per unit area/volume decreases as the area/volume in which sensors are deployed increases

5. CONCLUSION

In this paper, we have considered three models for deployment of sensors in a plane and in space i.e., hexagon, cube, hexagonal-prism, for testing the energy-efficiency (sensing and communication energy efficiency). In each model we have considered that neighboring sensing disks/spheres are meeting tangentially. Nodes are placed at the vertices of these configurations and the region inside the unit, not covered by the sensing disks/spheres placed at these vertices, is covered by sensing range of another node placed at the center of the unit. The node at center is of such a sensing range that it covers all the uncovered area/space. Analysis of the results reveals that the hexagon is the best in terms of sensing energy efficiency and the hexagon and hexagonal-prism are best in terms of communication energy efficiency. Overall we can say that hexagon is best in terms of energy-efficiency.

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Megha Sharma received the B.C.A and M.C.A degree from I.G.N.O.U in 2004 and 2008, respectively. She is currently working towards a Ph.D degree in computer Science at the Banasthali University of Rajasthan. Her research interests include wireless sensor networks with a focus on the coverage of wireless sensor networks.