On Coverage Determination and Exploiting Node Redundancy in Wireless Sensor Networks

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ABSTRACT

As selecting an appropriate number of nodes before Wireless Sensor Network deployment is important and it is difficult and inefficient to be done by simulation, a method for achieving that is requisite. This paper proposes simple mathematical equations to determine a suitable number of nodes for Wireless Sensor Network monitoring applications such that the essential node redundancy in Wireless Sensor Network could be exploited such that a good behavior with respect to lifetime, accuracy, fault tolerance, coverage, and connectivity is attained.
Keywords:- Wireless sensor network, coverage, node density, node redundancy, fault tolerance, connectivity

1. INTRODUCTION

In most Wireless Sensor Network (WSN) [1]–[3] applications the deployment of nodes is random not in engineered places and nodes remain unattended; this raises two issues, the necessity to achieve uniform distribution of nodes throughout the area and the node density and node redundancy for achieving accuracy, fault tolerance, preserving area coverage, or connectivity. These issues related to and can be adjusted by specifying a suitable count of nodes to be deployed. The determination of the required number of nodes beforehand aids in adjusting the node density, so that the node density will not be small in a way affects the just previously mentioned four design goals which results in less accurate received data and/or small useful lifetime, also the usage of a high density more than the need will increase the cost of the application and will not profit the application lifetime. The purpose of this paper is to propose equations for determining a suitable number of nodes to be deployed in a sensed region, where only the area of the region is known by using planimeter and a map of the area or an aerial photograph, high resolution photos by satellites such as using Google earth, wikimapia, and other applications, also the area can be determined by using a measuring Wheel passing on the actual land if applicable. The remainder of this paper is organized as follows. Section 2 reviews related work, section 3 discusses the proposed method and gives an illustrative example, section 4 explains the relation between the required lifetime and the number of deployed nodes, section 5 evaluates the proposed method, and section 6 concludes the paper and discusses the directions for future work.

2. RELATED WORK

Although a lot of network protocols' evaluations depend on testing the performance against increasing node density to determine the node density effect on the protocol behavior and determine the best node density for protocol performance to be used later in any protocol deployment for determining the count of nodes will be deployed, there are some works existing in literature for determining the number of nodes to be deployed in WSN regardless of the protocol used and independent on a specified node density, for example in [4], a general mathematical model is proposed to determine the number of nodes based on the required working time of WSN in general application. The model treats the collaborative signal processing (CSP) algorithms and network protocols for different applications as the parameters of energy consumption in each processing step; then it determines the number of nodes from these parameters. These parameters can be acquired through a simple simulation no matter what CSP algorithms and network protocols are used in the general situation. Rather than its calculation complexity, the authors put some restrictive assumptions for their model derivation, such as: the communication pattern of WSN is by clustering, there is one and only one interesting object in the field at anytime, its position is according to the uniform distribution in which only cluster with the interesting object is active, the other cells are not active, and they only consume energy to transmit data from the active cell to sink. In [5], the authors propose an equation to determine the minimal (optimal) sensor count necessary in each layer of a layered hexagonal WSN while keeping the desired network lifetime and coverage level. According to their equation, the necessary nodes count in each layer depends on the distance between two adjacent layers, the number of nodes from the outer layers which are connected to a node in the considered layer, the transmitting time for a node to transmit one packet, and the time period between two transmissions for the same node. They used the time division multiple access (TDMA) method for sharing the same channel among all active nodes, the number of active nodes required in the layer, the desired network lifetime, and the total energy available for each node (the same initial total energy for all nodes). But also this model uses restrictive assumptions restricts its use such as, assumed layered architecture, all nodes in the same layer consume the same energy, there is a specific distance between two layers, and the model considered only energy for transmitting data and not control packets. It doesn't specify a specific method to determine the number of active nodes required in the layer to achieve a desired coverage level. It assumes the backup nodes are placed at the same dying node position as the optimal position and this is not the case where it is difficult to be achieved in real deployments. In most of the existing works the problem of determining the number of nodes to be deployed isn't related as a separate issue, it is considered as a part of the coverage problem in WSN and correlates to a specific coverage method which is to extend the lifetime of the WSN by turning off redundant nodes and determining the number of active sensor nodes needed to cover the sensing area (may be with an expected coverage percent not necessary achieving full area coverage). The common approach of coverage methods is to schedule sensor nodes to work alternatively so that reduces the load on each node. Some of the existing strategies are used to determine the active nodes using the location information of the sensor nodes and their neighborhood such as [6], [7], but these strategies have the disadvantage of high cost with respect to energy consumption and money. Some coverage strategies are distributed and some others are centralized and accordingly location-aware. A general trend for some existing coverage strategies is to make the necessary nodes for achieving coverage in an active state and turns the redundant nodes to sleep state to extend lifetime. Of course this achieves coverage and saves energy but on the other hand it results in the redundancy controls the lifetime and not the lifetime controls the redundancy, and they didn't consider a way to preserve this coverage. In some strategies sensor nodes can utilize the number of neighbors within its sensing range to calculate its own probability of becoming a redundant node such as [8]. Most strategies depend on the sensing range, for example [9] proposes a mathematical method for coverage analysis of WSNs. An equation represents the coverage fraction depends on the ratio of the sensing range of a sensor node to the range of an entire circular deployment area, the number of deployed nodes in this area, and the degree of coverage required (k-cover). With given the ratio of the sensing range of a sensor node to the range of the deployment area, the number of the active nodes needed to reach the expected coverage can be derived. The deployment area considered in this model can be circular or square and it can represent a subset of the whole deployment area or represent the whole deployment area. Some protocols uses this model to achieve intra-cluster coverage technique such as [10], [11], where the coverage expectation is related to subset of the whole area which is the cluster in a clustered network, a cluster head randomly selects the count of nodes determined by this model from its member nodes as the active nodes and lets other nodes sleep.

3. THE APPROXIMATION TO DETERMINE THE SUITABLE NUMBER OF NODES

This section will illustrate the proposed mathematical equations and give a numerical example for its usage.

3.1 The proposed method

Assuming that, the sensed place is a surface with area (A), a number of nodes (N) are randomly and uniformly distributed throughout this area, and the nodes are homogeneous with respect to H.W. For assuring connectivity, increasing sensing accuracy and fault-tolerance, which is accordingly increasing the lifetime and full coverage time, at least a number of nodes (n) should exist in a certain range (r) from each active node corresponding to area (a) equals ($\pi \times r^2$), rather than the nodes shared with other active nodes ranges. The value of (r) can be chosen according to the node sensing capabilities and the nature of the sensed phenomenon. The phenomenon could be not distributed, continuously or discontinuously distributed. If the phenomenon is continuously distributed such as in temperature monitoring application, the value of (r) is chosen to be equal to the maximum sensing range a node supports or duplicates of it for achieving the four design goals. If the phenomenon is discontinuously distributed such as bridges' health monitoring, (r) is chosen to be equal to a small value to ensure there are a number of nodes will approximately sense the same value of the phenomenon at a point not for accuracy but for preserving coverage, fault-tolerance, and connectivity. Finally, if the phenomenon is not distributed such as patients' health monitoring in their beds, (r) is chosen to be equal to a relatively large value for achieving fault-tolerance and connectivity. The value of (n) is chosen as the user required may be with considerations for the required lifetime for the application, the maximum message length, the degree of accuracy required, etc. If we denote the area (a) as the coverage area of a node, the coverage areas are interleaved with a high degree due to dense deployment for full coverage therefore, (N) could not be determined from the equation $N = (A/a) \times n$, but we can approximate its value by considering a sensed region with a regular geometric shape such as the rectangular area as shown in Fig. 1, where the irregular regions are optimized to the most proximal geometric shape or divided into geometric shapes. In general, one can see any regular or irregular shape as an imperfect rectangle. By dividing the rectangle into equal square samples with edge equals (r), also assuming that in each vertex of each square sample there is a node for achieving full area coverage. In each vertex of the square samples, a node exists and each node of course represents a coverage area, i.e., one square sample represents four nodes and accordingly four coverage areas, while, two square samples don't represent eight coverage areas as shown Fig. 2, because there is an edge shared between the two samples, and the number of coverage areas resulted from a geometric shape sampling to tangent equal square samples where each vertex represents a node, cannot determined by just multiplying the square samples number by four. Above that, the position of the sample with respect to the others which differs from one sensed area shape to another results in different number of coverage areas as shown in Fig. 3. In Fig. (3.a), the sensed area shape entails the fourth square sample to be put such that it shares two edges with other samples, this results in nine coverage areas. Fig. (3.b) shows the sensed area shape entails the fourth square sample to be put such that it shares only one edge with another sample, this results in ten coverage areas.

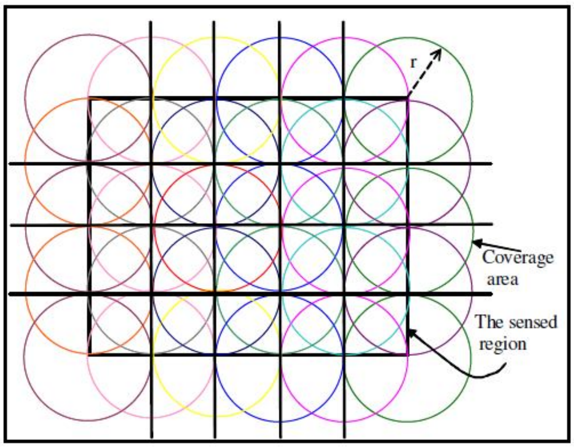


Figure 1 The model used in equations derivation for the sensed area

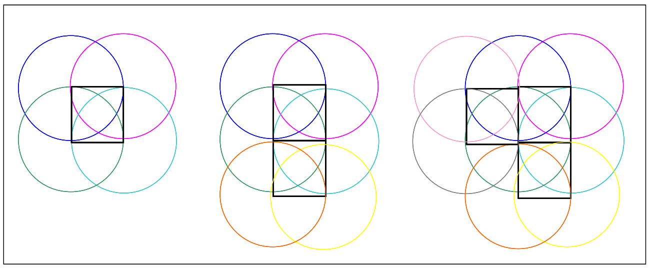


Figure 2 The coverage areas of one, two, and three adjacent square samples

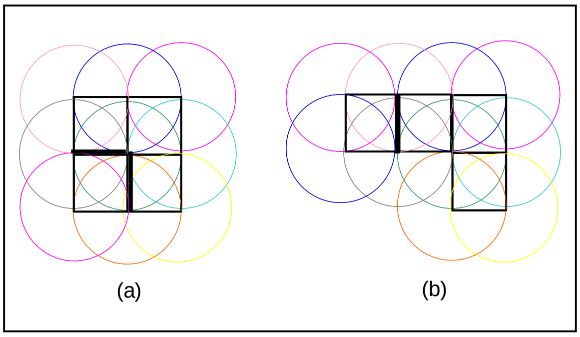


Figure 3 The difference in coverage areas count resulted from different placement of the same count of adjacent square samples

The same samples count may result in different number of coverage areas in two different area shapes and accordingly has a maximum and a minimum values for coverage areas number (CA) can be determined by equations were derived after some notes, considerations, and calculations as, the approximate count of square samples of A (Samples count) = A / (r × r). Let us denote (NCA) as the normal value of (CA) resulted from a samples count (SC) while (ACA) denotes the adjacent actual from the same (SC), then:

For maximum CA value calculation:

$$ACA = NCA - f(SC) = 4 \times SC - (SC + (SC - 2))$$

$$\therefore ACA_{max} = CA_{max} = (2 \times SC) + 2 \qquad (1)$$

For minimum CA value calculation:

$$RSC = \left(int\left(\sqrt{SC}\right)\right)^2 + \left(2 \times int\left(\sqrt{SC}\right)\right) + 1$$

$$= \left(int\left(\sqrt{SC}\right) + 1\right)^2 \qquad (2)$$

where, RSC: a reference samples count which is the SC corresponding to a square shape quite fits to the adjacent samples starting from the value 4 (i.e., 2×2, 3×3, 4×4, 5×5, and so on). int(z), means the integer value of the fractional number z.

$$CA_{RSC} = RSC + 2 \times \sqrt{RSC} + 1 \qquad (3)$$

where, CA_{RSC} : the CA value corresponding to RSC

If $(RSC - SC) < \sqrt{RSC}$, then,

$$CA_{min} = CA_{RSC} - (RSC - SC) \qquad (4)$$

Else,

$$CA_{min} = CA_{RSC} - (RSC - SC) - 1 \qquad (5)$$

With the notice that, if the SC is itself an RSC (i.e., its square root is an integer value), then its CA_{min} is determined directly from equation (3).

Then the approximate value of CA corresponding to an area A regardless of its shape can be determined as a minimum value from equations (3) or (4) or (5), especially that the model upon which the derived equations gives more than the need in a realistic model, it ensures that each point in the sensed area is sensed by at least two nodes in addition to the count of nodes (n) mentioned previously that should exist in each node range and respective to it; also the maximum value of CA can be considered as the CA especially when the sensed area is narrow and long. Also we can take the minimum and maximum values of CA into account to determine its value as the average value.

$$CA = \frac{CA_{min} + CA_{max}}{2} \qquad (6)$$

$$N = n \times CA \qquad (7)$$

An alternative method to determine CA without calculating and using the two extreme values can be described by the following equations:

For even SC: $ACA = NCA - f(SC)$

$$= 4 \times SC - (SC + \text{the number of the SC in even numbers sequence} \times 3) = 4 \times SC - (SC + (\frac{SC}{2} - 1) \times 3)$$

$$\therefore ACA\,|_{even\ SC} = CA.\,|_{even\ SC} = \frac{3}{2} \times SC + 3 \qquad (8)$$

For odd SC, excluding 1: $ACA = NCA - f(SC)$

$$= 4 \times SC - (SC + (\frac{SC - 3}{2}) \times 3 + 1)$$

$$\therefore ACA\,|_{odd\,SC} = CA\,|_{odd\,SC} = \frac{3}{2} \times SC + \frac{7}{2} \qquad (9)$$

The alternative method determines a CA value between the two extremes can be taken as the actual CA exists.

3.2 An illustrative example

Consider the map of the land segment shown in Fig. 4, by using a graph paper for area calculation, the land area equals 1423.442 m^2, means A =1423.442 m^2, with r = 3m and n = 3, SC = $1423.442/(3 \times 3) = 158.16 \sim 158$.

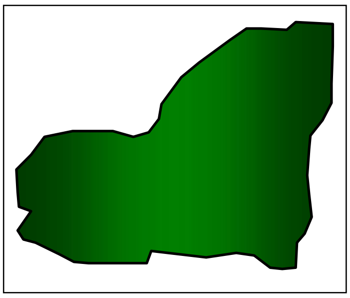
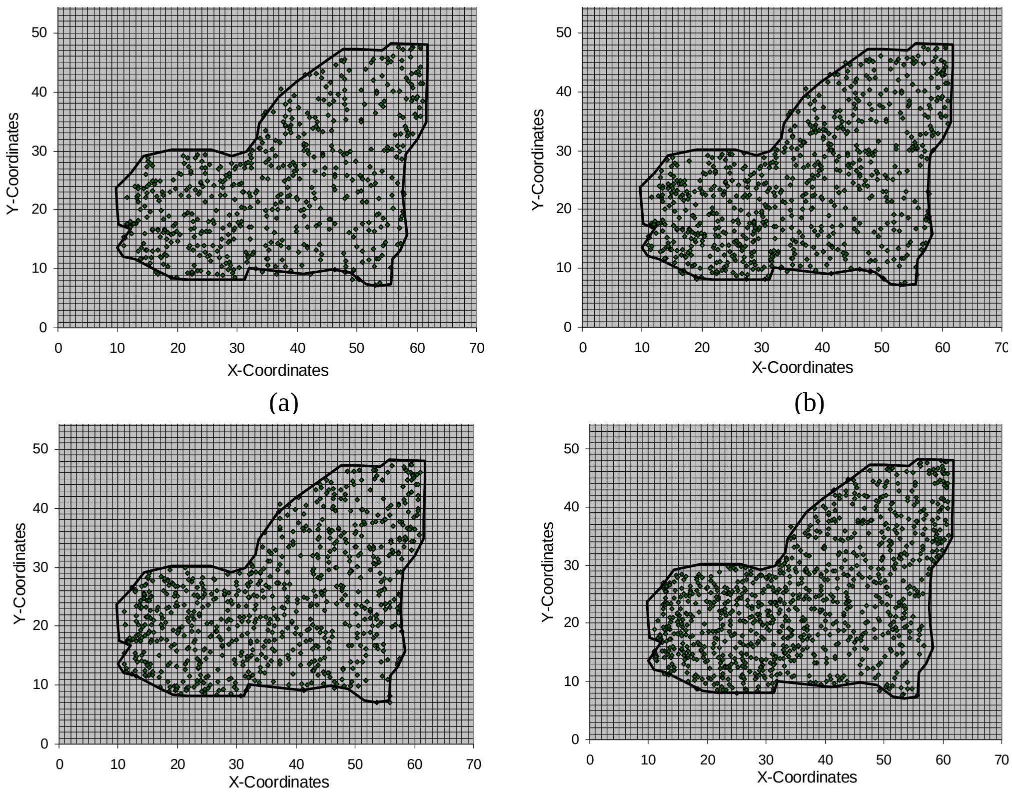


Figure 4 The irregular area used in the example

Applying equation (1), $CA_{max} = 2 \times 158 + 2 = 318$, and by applying equation (4), $CA_{min} = 196 - (169 - 158) = 185$, while the Average CA = 251.5 ~ 252, using equation (6).
To determine intermediate CA value, using equation (8)
$CA\,|_{\text{even SC}} = (3/2) \times 158 + 3 = 240$
Therefore, from equation (7)
$N = [318 \times 3, 185 \times 3, 252 \times 3, 240 \times 3] = [954, 555, 756, 720]$
By deploying the four possibilities for nodes count randomly and uniformly through the same area as shown in Fig. 5. It can be seen that with random and uniform distribution, the minimum number of nodes may result in uncovered or slightly covered regions, the average and intermediate nodes count result in better distribution, while the maximum nodes count also results in good distribution as well, but there may be redundant useful nodes especially that the area is not narrow which is the ideal shape for considering the maximum value.



(c) (d)

Figure 5 Different nodes' count deployment, a) minimum count, b) intermediate count, c) average count, d) maximum count

Fig 6, shows the nodes count calculation of another example to show the relation to area from the aforementioned equations. The minimum, maximum, average, and intermediate values with the same parameters for the previous example, but with different areas are drawn. The curves represent the maximum, minimum, average, and intermediate values for nodes count are linear or approximately linear, so for calculation simplicity, we can represent them by straight line equations (a straight line equation for each N calculation method for each r and n values), for example of minimum value calculation:

$N_{max} = 0.6658 \times A + 5.82,$ for r=3 and n=3

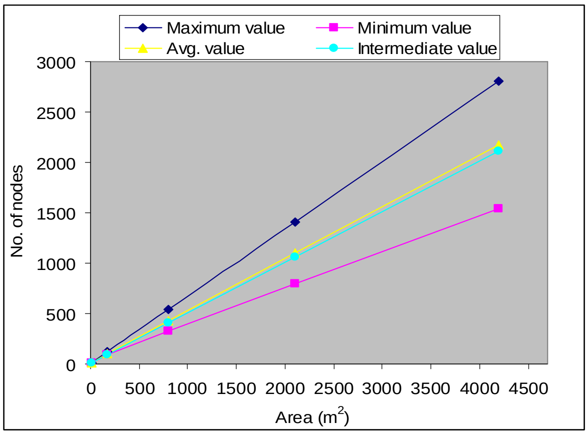


Figure 6 Nodes count versus different areas

These straight line equations give the value of N for the different values of A but with a small error percentage from the value of N calculated by the previous method.

4. LIFETIME RELATION TO NODES COUNT

This determination method of suitable number of nodes for WSN deployments provides some network performance metrics such as accuracy, fault tolerance, full area coverage, or connectivity with the assumptions, that the network setup and used protocols know how to take advantages. The network protocols behave such that it can exploit and deal with the taken confined node redundancy to achieve these metrics, preserve full area coverage, and extend lifetime. Therefore, to benefit from the estimated nodes count for the network, one must use a coverage method such that the network works with only the number of nodes entails and the required accuracy, which realize the full coverage as the aforementioned coverage model (this number corresponding to n=1) and for every node dies, then another node in its coverage area is activated; the degree of accuracy and the number of alternative nodes for each active node which are its coverage area neighbours is determined by the value of n, as indoors depends on the value of r and the required lifetime. We could say that, the network life is composed of almost symmetric faces; each face represents a full covered network. The first face consists of the first group of nodes turned to active state, the second face consists of their first alternatives, the third face consists of their third alternatives, and so on. These faces are successive and overlapped; the face begins with the death of the first node in its anterior and ends with the death of its last node, except the first face begins with the network deployment and the last face ends with the surceasing of data arrival at the sink, not necessary with the death of the last node. The overlap between two faces represents the degradation of the first face which is the time from the death of its first node to the time of the death of its last node. The number of overlapped faces constitutes the network lifetime which is determined by the value of n. For the four overlapped faces depicted in Fig. 7, L indicates the network lifetime which can be computed by equation (10):

$$L = T_{f1} - T_{d1} + T_{f2} - T_{d2} + T_{f3} - T_{d3} + T_{f4} \qquad (10)$$

And accordingly for x faces network:

$$L = \sum_{i=1}^{x} T_{fi} - \sum_{j=1}^{x-1} T_{dj} \qquad (11)$$

where, T_1 is the time at which the first node in the first face, and accordingly in the network, dead. T_{fi} and T_{dj} are the lifetime period and degradation period of each face respectively.

If it is assumed that all T_{fx} are equal and countervailed approximately to the one face network lifetime (T_{fo}), and all T_{dx} are equal and countervailed approximately to the degradation time of one face network (T_{do}), then, by substituting in equation (11), the x value can be obtained as:

$$x = n_{coverage} = \frac{L - T_{do}}{T_{fo} - T_{do}} \quad (12)$$

Means, (n), the number of nodes needed to be deployed in the coverage range of a node, can be decomposed to the count of nodes needed for achieving a required accuracy($n_{accuracy}$), and the count of nodes needed for preserving full coverage ($n_{coverage}$) which equals to the number of faces x.

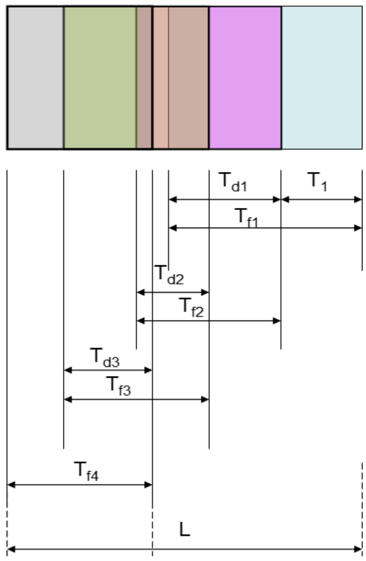


Figure 7 The four faces network used in the example

From equation (12), a value for $n_{coverage}$ suitable for reaching a lifetime L can be determined, then with the required value of $n_{accuracy}$, n can be computed as ($n = n_{coverage} \times n_{accuracy}$), and from equation (7) and equation (1), (3),(4),(5),(6),(8),or (9), the value of N can be determined. Again, it worth noting that, to seek for ultimate benefit from this method of determining N value, it is the responsibility of the implemented network protocol to take advantage of redundant nodes for achieving fault tolerance and connectivity and it is responsible to be energy-efficient to increase T_{fo} to decrease $n_{coverage}$. It is also the responsibility of the implemented coverage method to realize the basic principle of coverage the computation based on, which entails that the coverage area neighbours of an essentially active node represent relative to it the burrow it defects to do its work only when it is going to stop work. Based on that, the essential number of nodes for full coverage is preserved in the same time the energy of inessential nodes is also preserved and the scheduling overload is reduced; also it is the responsibility of the coverage method to be efficient doesn't result in nodes remain inactive useless until lifetime end, suitable for node deletion due to different reasons, and should require a small control messages count.

5. METHOD TEST AND EVALUATION

The simulation runs were conducted using the discrete event simulator OMNeT++ [12] as the simulation platform to generate a network in $30 \times 30\ m^2$ area in which sensor nodes are distributed randomly, statically, and uniformly. The network used to evaluate the method proposed in this paper for computing the suitable nodes count uses the LEACH protocol [13] which is one of the first important routing protocols as an example of a WSN network with the parameters' values shown in table (1), and assumptions as follows:

- There is only one sink in the field, which is deployed at a fixed place outside the area.
- Sensor nodes are location-unaware, non-rechargeable, and always have data to send.
- The node can vary its transmission power depending on the distance to the receiver.
- For simplicity, it is assumed that the probability of signal collision and interference in the wireless channel is ignorable and the radio transmitter, radio amplifier and data fusion unit are the main energy consumers of a sensor node.
- The Radio H.W. energy dissipation model used is as in [14].
- The consumed energy in aggregating *M* *k*-bit signals into a single *k*-bit signal = $M \times E_{DA} \times k$, where: E_{DA} denotes

the energy consumed by data fusion.

- There are five cycles in each round.
- Node deletion from the network is mainly due to energy depletion, and infrequently due to other factors, so can be ignorable.

Table 1: Simulation parameters

Parameter	**Value**
Network field	(30,30)
r	5 m
Sink position	(15,60)
Initial energy	2.5 J
Data packet size	525 Bytes
Broadcast packet size	25 Bytes
E_{DA}	5 nJ/bit/signal
$n_{accuracy}$	1

A coverage method is added to LEACH network to satisfy the previously mentioned basic principle, upon this method the nodes, which have count equals N, are divided before deployment into groups each group corresponding to a network face, so the count of nodes in each group equals the essential number of nodes ($n_{face} = CA \times n_{accuracy}$), a member node in a group (dedicated to work in a certain face) is identified by its ID, where the first n_{face} nodes starting from ID = 0 work in the first face, the second n_{face} nodes starting from ID = n_{face} work in the second face, and so on. Each group of nodes distributed independently uniformly throughout the whole sensed area. The values of n_{face} , $n_{coverage}$, and r are inputs to the protocol. The CA used in this evaluation is the intermediate value calculated from equation (8). When the node detects that it will go out the network soon, first it tries to activate one of the nodes in its directly subsequent face, if it didn't find one in its neighbourhood alive and inactive, it tries to activate an alive and inactive node in its face or a later face, except the first face of course, if it didn't find one, it finally tries to activate a node in a face subsequent to its directly next face. The performance of LEACH with the proposed coverage is compared to the normal LEACH and LEACH with intra-cluster coverage upon which the cluster head selects randomly a constant number of nodes from its cluster members to be active. Fig. 8, illustrates the effect of the proposed method of determining the suitable number of nodes and the proposed coverage method it evokes in increasing the lifetime at different deployed nodes counts increasing gradually with a fixed step equals 25 nodes. As shown in Fig. 8, the lifetime is increased by about 77.37 %, 69.33%, and 58.66% from normal LEACH, LEACH with intra-cluster with constant selected nodes count equals 19 and 9 respectively. In random selection intra-cluster coverage method, the inactive nodes only exempted from data sending, but they participate in network setup and they send during it control messages each round for their states to be determined, whether a node will be active or inactive during the current round. The reference lifetime and degradation time T_{fo} and T_{do} are reported for one face network to be 5.31 and 3.21 days respectively. Fig. 9, represents the count of nodes required to reach a specific lifetime versus the required lifetime for LEACH with the proposed method, the suitable value of $n_{coverage}$ is determined by equation (12). For normal LEACH, the increasing of nodes count doesn't affect the lifetime or inversely affects it, for example at 1000 node the lifetime is 4.17 days and at 2000 node the lifetime is 2.48 days, the same for LEACH with intra-cluster coverage with 19 and 9 active members.

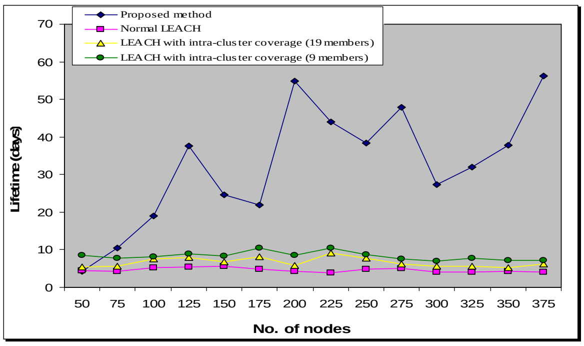


Figure 8 Lifetime versus number of deployed nodes

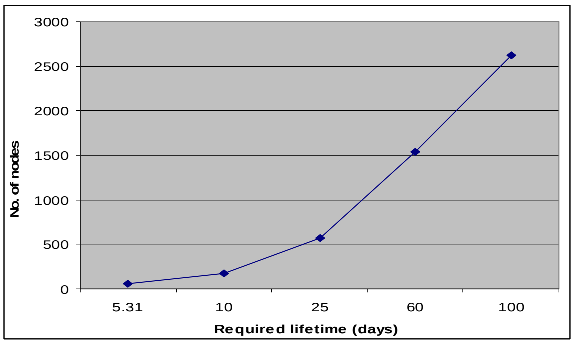


Figure 9 Number of nodes versus required lifetime

Fig. 10, represents the determined count of nodes to reach the required lifetime for LEACH with the proposed method and the actually reached lifetime, it is obvious that the actually reached lifetime is more than the required, but in reality it is not more than the required because the required lifetime means to achieve good coverage percentage until the end of a specific period which is the required lifetime. For example, Fig. (11.a) represents the covered area at the end of the required lifetime for 100 days network corresponding to LEACH with the proposed method, while Fig. (11.b), Fig. (11.c), and Fig. (11.d) represent the covered areas in half of the maximum lifetime reached in Fig. 8 by normal LEACH and LEACH with intra-cluster coverage.

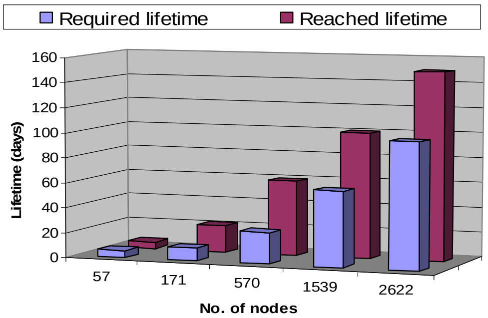


Figure 10 The required lifetime and reached lifetime versus number of nodes for LEACH with the proposed method

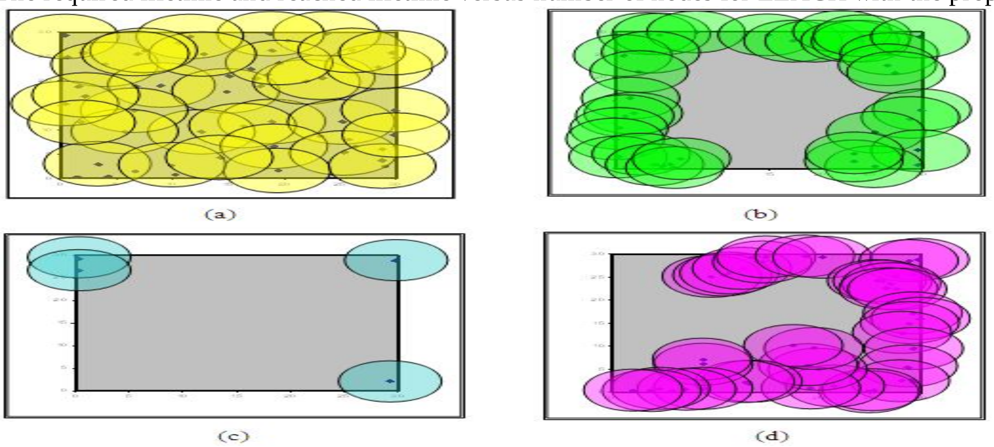


Figure 11 The covered and uncovered regions, a) for LEACH with the proposed method at the day number 100 for required lifetime 100 day, b) for half lifetime of normal LEACH, c) for half lifetime of 19 member intra-cluster coverage LEACH, and d) for half lifetime of 9 member intra-cluster coverage LEACH

6. CONCLUSIONS AND FUTURE WORK

This paper proposes a model of equations for determining a suitable number of nodes to be deployed for a WSN monitoring applications for a given area and shows how this model can be used to efficiently reach a specific lifetime. This method has some advantages, it offers to the implemented protocol, accuracy with a specified degree, fault tolerance, connectivity, full area coverage (with high degree reaches each point in the area is approximately covered by at least two nodes which may be considered as tolerance to the used protocols inefficient behaviour and inefficient uniform distribution of nodes), reaching the required lifetime, preserving full coverage along lifetime, controllable behaviour with respect to lifetime, determining the suitable count of nodes before real deployment, avoiding costly testbeds and extensive simulations which includes large number of nodes and full battery capacity as initial energy for that large number which requires high H.W. capabilities and long simulation period (it is sufficient to test the network for one face or at most two faces to determine without testing the suitable number of nodes for any required lifetime). It is localized and distributed and does not require pre-knowledge of sensor nodes' locations. It is simple where it uses very simple mathematical equations far from integral and differential calculus and probabilities. It results in better coverage and it reduces the scheduling overhead as well therefore, better use of redundant nodes energy can be provided. It also saves money with respect to the number of nodes and nodes H.W. capabilities (no need for GPS or directional antenna). It is not necessary to be related to the area coverage, since the value of r is not necessary to be equal or related to the sensing range. Moreover, if r selected to be related to the sensing range, i.e. it is meant by it area coverage, it is not restricted to a specific coverage method, but considers general guidelines for the coverage method uses it. Finally, the proposed method or its methodizing with different original models for equations derivation can be widely applied to designing different WSN protocols and also fit to existing protocols. The proposed method is still needed to be tested may be with different original derivation models for different protocols, different applications, and against different methods of coverage; also it should be exploited to design new protocols benefit from its advantages and result in overall good behaviour.

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