Energy Efficient Deployment and Scheduling of Nodes in Wireless Sensor Networks

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***Abstract*—Wireless sensor networks being energy constrained systems, one major problem is to deploy the sensor nodes in such a manner so as to ensure maximum coverage and connectivity with optimal number of nodes and furthermore elongate network lifetime with maximum energy utilization. In this paper, the above problem has been tackled for a linear array and the concept has been extended to two-dimensional array of sensor nodes. A node deployment strategy has been devised which ensures equal energy dissipation for all the nodes through a trade-off between idle and sleep times while ensuring minimal energy dissipation for the entire network during each data gathering cycle. Furthermore the deployment scheme being developed for equidistant placement of nodes, a 100 percent coverage and connectivity has been guaranteed with radio ranges remaining within appreciable limits. Extensive simulations have been carried out with encouraging outcomes and the results that have been obtained show that the network lifetime is also enhanced compared to previous schemes.**

***Keywords*— Wireless sensor networks, coverage, connectivity, equal energy dissipation, idle and sleep times.**

I. INTRODUCTION

Wireless sensor networks can be considered as a collection of mobile or static nodes capable of communicating with each other without any prior infrastructure along with the potential to collect data more cost-effectively, autonomously and robustly as compared to a few macro sensors [1,2]. Recent improvements in efficient and affordable integrated electronic devices, digital signal processors and short-range radio electronics have led to the evolution of wireless sensor networks as a special type of wireless embedded networks. Sensor networks are widely used in a variety of applications such as seismic, acoustic, climatic data gathering, environmental monitoring, surveillance and national security, military and health care etc. These integrated nodes are wireless and hence are highly energy constrained. Replenishing the batteries for thousands of deployed nodes is also an unfeasible proposition. So it is essential that suitable energy-efficient schemes be devised so that post-deployment lifetime is enhanced. Furthermore it is observed that in many energy efficient strategies [3], full coverage demands an impractically large radio-range with increasing number of nodes which is a practical backlog. Hence it is the need of the hour to obtain an optimal balance of energy-efficiency, lifetime, coverage and connectivity.

Attempts for energy optimization have been made in [1] where optimal spacing of nodes for minimal energy dissipation of the network has been considered. However the energy dissipation of the individual nodes determining network lifetime has been overlooked. In [4] the author has tried to achieve equal energy dissipation of nodes but has only considered energies involved in transmitting packets of information neglecting energies involved in receiving and idle states. An outline for the maximum lifetime of a sensor network has been laid down in [2] considering that only a single node is generating packet of information while all the other nodes simply act as relays. Consideration for a two-dimensional network appears in [5] where lifetime maximization has gained precedence, again by minimizing the total energy of the network. Analysis involving transmitting, receiving and idle states has been performed in [3] where characteristic distance and variable radio ranges has been suggested as means for minimizing energy dissipation. In [6] though energy dissipation has been balanced, redundancy and coverage problems come into play. On the other hand [7] is a survey which just highlights the various issues of wireless sensor networks. In this paper, we develop a node deployment strategy and determine the number of nodes and the sensing range of each node in order to cover a given distance so that full energy utilization is achieved. Furthermore energy dissipation for the entire network is minimized during each data gathering cycle and a policy for balancing idle and sleep states of each node has been devised. This deployment scheme ensures full coverage and connectivity and is thus an improvement upon previous works in these respects.

II. ENERGY DISSIPATION MODEL

We consider each data gathering cycle of duration T_d to be divided into four states for all the nodes – the transmitting, receiving, idle and sleep states. A modified energy dissipation model for radio communication similar to [1,3] has been assumed. The energy required for transmission per second is thus given by

$$E_{t,i}=e_t+e_d\, d^n \tag{1}$$

where e_t is the energy dissipated in the transmitter electronic circuitry per second and $e_d d^n$ is the amount of energy required per second to transmit data packets satisfactorily over a distance d and n is the path loss exponent (usually $2.0 \le n \le 4.0$). The distance 'd' is chosen such a way that it is less than or equal to the radio range ($\mathbf{R_{radio}}$), which is maximum internodal separation for successful communication between two nodes. If T_1 is the time required to successfully transmit a packet over a distance d then total energy to transmit a packet is

$$E_t=(e_t+e_d\, d^n).T_1 \tag{2}$$

If e_r is the energy required per second for successful reception and if T_2 is the total time required to receive a packet then the total energy to receive a packet is

$$E_r=e_r\, .T_2 \tag{3}$$

Let e_{id} be the energy spent per second by the nodes in the idle state and T_3 be the time spent in the idle state, then,

$$E_{id} = e_{id}\, T_3 \tag{4}$$

The remaining part of the data gathering cycle is spent in sleep state of duration T_4 , where the energy dissipation of each node is minimum and can be approximated as zero. However analysis for finite energy spent in dissipation during the sleep state has also been carried out for concrete understanding. The performance-measuring parameters, which have been enhanced in our scheme, are the coverage fraction (χ) and the energy utilization ratio (η). The coverage fraction for a collinear array is the ratio of the total distance sensed by the nodes to the total distance required to be covered by the network while for a two-dimensional array it is the ratio of the total area sensed by the nodes to the total area required to be sensed by the nodes. The energy utilization ratio may be defined as the fraction of the total initial energy at the time of deployment that is consumed when the network dies i.e. when a single node in the network becomes non-functional so that relay is no longer possible. Thus the energy utilization ratio (η) = (E_{used}/E_T)*100% where E_{used} is the total energy utilized by the network during its lifetime and E_T is the total energy of the nodes at the time of deployment.

III. Condition for Equal Energy Dissipation in a Linear Array of Nodes

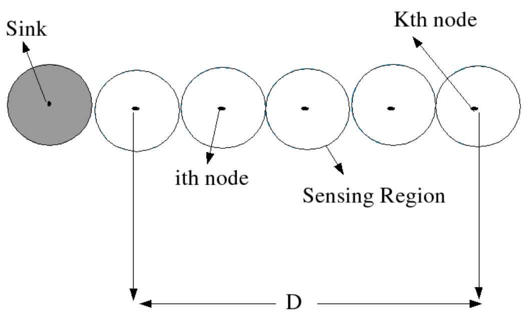

Fig. 1. Linear array of nodes

A collinear system of K wireless sensor nodes is considered with the sink at one end (Fig. 1). The nodes are placed equidistant from one another, with the radio range (**R_{radio}**) twice the sensing range (**r_s**) so that maximum coverage fraction (χ = 100%) can be achieved ensuring connectivity. The systems is now modeled in such a way that equal energy dissipation during each data gathering cycle is achieved by adjusting the idle and sleep times of the individual nodes. Let the spacing between any two consecutive nodes be 'd' units. Hence for the total distance 'D' to be covered by all the nodes, we have (K-1).d=D. We further place the sink at a distance of ‘d’ from the first node. We assume that during the entire data gathering cycle of duration T_d, each node generates one data packet (say 'B' bits). All nodes send data packets to the sink by forwarding the set of received packets (from nodes away from the sink) along with its locally generated packet to its nearest neighbor towards the sink as a repeater (nearest neighbor routing). Every node does four major functions during the each data gathering cycle as mentioned in Section II.

Let E_o be the initial energy of each node in the linear array.If ‘E_i’ is the energy consumed by the i^{th} node in a data gathering cycle, then we have,

$$E_i = E_t(K-i+1) + E_r(K-i) + E_{id}$$
$$= (e_t+e_d d^n)(K-i+1)T_1 + e_r(K-i)T_2 + e_{id}T_{3i} \tag{5}$$

We choose a reference node ‘i_{ref}’ in order to determine the idle time of the different nodes.

$$E_{iref} = (e_t+e_d d^n)(K- i_{ref} +1)T_1 + e_r(K- i_{ref})T_2 + e_{id}T_{3iref} \tag{6}$$

To ensure equal energy dissipation by all nodes the condition $E_i = E_{iref}$ should be satisfied for $1 \le i \le K$. Therefore,

$$(e_t+e_d d^n)(K-i+1)T_1 + e_r(K-i)T_2 + e_{id}T_{3i} = (e_t+ e_d d^n)T_1(K- i_{ref} +1) + e_r(K- i_{ref})T_2 + e_{id}T_{3\,iref} \tag{7}$$

Taking $(e_t+e_d d^n)/e_{id} = x$ and $e_r/e_{id} = y$, we get,

$$T_{3i} = T_{3\,iref} + (xT_1+yT_2)(i- i_{ref}) \tag{8}$$

Thus the determination of the idle time for the reference node enables the calculation of the idle times for all the other nodes in the network. To ensure that the data gathering cycle T_d remains same for all the nodes, they must be assigned different durations of sleep. Thus for the i^{th} node we have,

$$T_{4i} = T_d - (K-i+1)T_1 - (K-i)T_2 - T_{3i} \tag{9}$$

where T_{4i} is the duration of sleep for the i^{th} node. To guarantee that all nodes in the topology have non-zero sleep time, the following inequality must be satisfied.

$$T_d > \max\,[(K-i+1)T_1 + (K-i)T_2 + T_{3\,iref} + (xT_1+yT_2)(i- i_{ref})] \tag{10}$$

Moreover if a node has a capacity of handling at most ‘P’ packets per second then, $T_d > K/P$. It can be found that the expression

$$(K-i+1)T_1 + (K-i)T_2 + T_{3\,iref} + (x\,T_1+y\,T_2)(i- i_{ref})$$

is maximum for the K^{th} node, irrespective of the choice of the reference node. Among this set of maximas of the above expression obtained due to all selections of the reference node, it is now desirable that we find out that reference node for which it attains its minima. Assuming x,y >1, inspection of the above relation reveals that it is best to choose the reference as the K^{th} node as it provides the least duration of active time.

IV. Optimizing the Number of Nodes in a Given Distance Considering Minimum Energy Dissipation During a Data Gathering Cycle

The total energy dissipated by the network during each data gathering cycle E_{tot} is given by,

$$E_{tot} = (e_t + e_d d^n)T_1K^2 + e_rT_2(K^2 - K) + e_{id}KT_{idlemin} \tag{11}$$

where $T_{idlemin}$ is the minimum idle time among the nodes of the network which is also the time for which the first node must remain idle for dealing with requisite number of packets.

$$\frac{dE_{tot}}{dk} = 2Ke_tT_1 + \frac{e_dD^nT_1(2K(K-1)+nK^2)}{(K-1)^{n-1}} + (2K-1)e_rT_2 + e_{id}T_{idlemin} \tag{12}$$

Taking $T_1 = T_2$ and n = 2

$$\frac{2KD^2}{(K-1)^3} - 2Kb = a \tag{13}$$

where ,

$b = (e_r+e_t)/e_d$ and $a=(e_{id}T_{idlemin} - e_rT_1)/(T_1e_d)$

The optimal value of K is obtained by MATLAB Simulation. The simulation is performed with data rate of 20 kbps as the commercially available motes have comparable data rates. The values of the different parameters used in the simulation are e_t = 1024 μJ/s, e_r = 819.2 μJ/s, e_d = 2048 μJ/m^2/s, e_{id} = 409.6 μJ/s. Considering the model given in [3], and modifying it accordingly to suit our scheme, we take the values of e_t, e_r, e_{id} as mentioned above. The optimum value of K thus obtained for D = 6000 m is 141 (taken to the nearest integer). The internodal spacing d = 42.8 m. The times T_d and $T_{sleepmax}$ are 77.9 s and 40.9 s respectively where $T_{sleepmax}$ is the maximum sleep time among all the nodes in the network. With D = 3000 m we get the optimal value of K as 74.

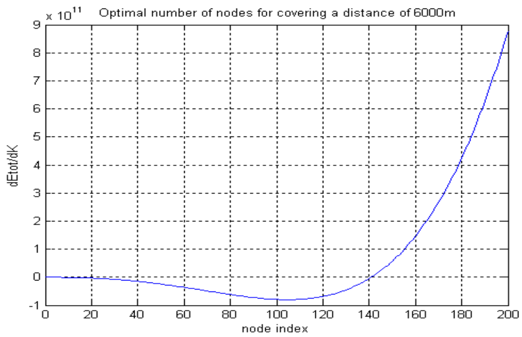

FIG. 2. Solution for optimal value of K for D = 6000 m

V. SCHEDULING OF SLEEP AND IDLE TIMES CONSIDERING FINITE ENERGY IN THE SLEEP STATE

A more realistic situation is now considered in which the sensor node dissipates a small, yet finite amount of energy in the sleep state. Let e_s be the amount of energy dissipated in the sleep state per second by a node. The system is remodeled ensuring equal energy dissipation of all the nodes in a data gathering cycle. As a result the energy utilization ratio turns out to be 100%. Therefore we have,

$$E_i = (e_t+e_d d^n)(K-i+1)T_1 + e_r(K-i)T_2 + e_{id}T_{3i} + (T_d - (K-i+1)T_1 - (K-i)T_2 - T_{3i})e_s \qquad (14)$$

For $E_i = E_{iref}$, $1 \le i \le K$ and performing the analysis as in section III, we get,

$$T_{3i} = T_{3iref} + [(x-z)T_1 + (y-z)T_2](i-i_{ref})/(1-z) \qquad (15)$$

where $z = \frac{e_s}{e_{id}}$. Similar analysis as done in section III shows that in this case also the Kth node should be taken as the reference.

VI. RANDOM PLACEMENT OF THE NODES

It is practically very cumbersome to deploy nodes in an exactly equidistant manner and as a result some amount of randomness exists in the position of a sensor node about the exact location of placement. In this section we consider one case of random placement where the sensor node location is uniformly distributed within a finite region around the exact placement location. Let x_i denote the position of the ith node from the sink considering equidistant node placement. Hence $x_i = i \times d$. We assume that each node has an equal probability of being placed at all points lying within distances 'd/2' on either side of x_i. If Y_i is the random variable denoting the position of the ith node then, its pdf can be found out to be,

$$f_{Y_i}(y_i) = \frac{1}{d}, \quad x_i - \frac{d}{2} \le y_i \le x_i + \frac{d}{2}; \qquad = 0 \quad \text{otherwise} \qquad (16)$$

Similarly $f_{Y_{i-1}}(y_{i-1})$ can also be determined.

Let Z_i be the random variable denoting the internodal distance between the ith and (i-1)th node. Thus we have,

$$Z_i = Y_i, \quad i = 1; \qquad = Y_i - Y_{i-1}, \quad 2 \le i \le K \qquad (17)$$

Thus we get,

For i = 1

$$f_{Z_i}(z_i) = \frac{1}{d}, \quad \frac{d}{2} \le z_i \le \frac{3d}{2}; \qquad = 0, \quad \text{otherwise} \qquad (18)$$

For 2≤ i ≤ K

$$f_{Z_i}(z_i) = \frac{z_i}{d^2}, \quad 0 \le z_i \le d; \qquad = \frac{2}{d} - \frac{z_i}{d^2}, \quad d \le z_i \le 2d; \qquad = 0 \quad \text{otherwise} \qquad (19)$$

Let ε_i be the random variable denoting energy dissipated by the ith node in one data gathering cycle. Therefore,

$$e_i = e_{1i} + a_i.z_i^n \qquad (20)$$

where $e_{1i} = e_t(K-i+1)T_1 + e_r T_2(K-i) + e_{id}T_{3i}$
and $a_i = e_d T_1(K-i+1)$

Next by evaluating the pdf of ε_I we calculate its mean .
The mean value of ε_i is $\overline{e_i}$ where $\overline{e_i}$ is

$$e_{1i} + \frac{a_i d^n(3^{n+1}-1)}{2^{n+1}(n+1)} \quad \text{for i=1}$$

$$\left[\frac{e_{1i}}{2} + \frac{a_i d^n}{n+2}\right] + 2\left[e_{1i} + \frac{a_i d^n(2^{n+1}-1)}{n+1}\right] - \left[\frac{3e_{1i}}{2} + \frac{a_i d^n(2^{n+2}-1)}{n+2}\right] \quad \text{for } 2 \le i \le K \qquad (21)$$

VII. EXTENSION TO TWO DIMENSIONS

For extending the situation to a two-dimensional scenario, a rectangular region is considered which is covered with linear arrays of nodes placed one above the other, as illustrated in Fig. 3.

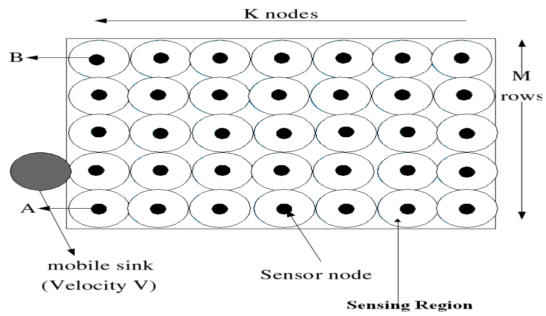

Fig. 3. Two-dimensional array of nodes

Let us assume that there are K nodes in each linear array and let there be M such arrays. Therefore the total area of interest is $4MKr_s^2$ where 'r_s' denotes the sensing range of each node. As considered earlier in section III, all nodes in any linear array relay information from the source to the sink. But unlike the case of a single linear array where we had a fixed sink, here we consider a mobile sink which collects the necessary information from the terminal node of each linear array. As KT_1 is the time required by the terminal node to transfer all data packets to the sink and the velocity of the sink in 'V', therefore the time required by the sink to move from one linear array to another and collect all the data packets of the corresponding array is $T^/ = KT_1+(2\ r_s\ /\ V)$. Thus if there be M linear arrays in all, the total time required to navigate from A to B is $T = (M-1)T^/$. The mobile sink starts from A, moves to B and then returns back to A thereby completing a cycle. This process is repeated continuously. At the onset of each such cycle during the sink's motion from A to B the i^{th} array of nodes sleeps for a time $(i-1)T^/$ and then begins its data gathering cycle. This is done so that the terminal node of the i^{th} array has just sufficient time left in its data gathering cycle to successfully transfer the gathered packets to the mobile sink upon its arrival after a time $(i-1)T^/+T_d-KT_1$. After the completion of a data gathering cycle of the i^{th} row of nodes, it is assigned an additional sleep time of $(M-i)T^/$ till the sink reaches B. During the sink's motion from B to A the i^{th} row initially sleeps for a time $(M-i)T^/$. It then begins its data gathering cycle and once again sleeps for a time duration of $(i-1)T^/$. Thus we observe that every data gathering cycle of duration T_d seconds is accompanied by an additional time duration of $(M-1)T^/$ and this is true for all the linear arrays covering the two dimensional plane. It has already been stated in section III that for any linear array for nodes there is 100% energy utilization. For extending the problem to a two dimensional case, only an additional time $(M-1)T^/$ is included for all the nodes in the network during which the nodes are assigned to sleep, thus eliminating energy dissipation during this period which not only ensures 100% energy utilization but also improves the network lifetime.

We define a new parameter called percent extratime given by

$$P_{Xtime} = (M-1)T^/ / T_d$$

$$\text{or,} \quad P_{Xtime} = (M-1)(KT_1+2r_s/V)/ T_d \qquad (22)$$

Thus we observe that by increasing the speed 'V' of the mobile sink we can reduce this extra time incorporated to ensure no data accumulation and complete energy utilization. Furthermore although the coverage fraction (χ) in the deployed arrangement is 78.4%, yet 100% informational coverage can be achieved provided certain conditions are satisfied. We consider a simple system where we consider that a sensing signal of amplitude A_m decays with distance according to the relation $A_m = A_{m0}e^{-\alpha d}$ where α denotes decay per unit distance. In order to detect a signal by the receiver, its magnitude must be greater than some threshold value A_{th}. To ensure that our system has 100% informational coverage we need to design the sensing and radio range in such a way that

$$A_{m\min} = A_{th}e^{-\alpha r_s} \qquad (23)$$

where A_{mmin} is the minimum amplitude of the physical quantity that is required to be sensed by the network and A_{th} is the minimum value of the physical quantity that can be sensed by any of the sensors. For example considering a sensor network deployed in order to sense some kind of vibration (e.g. earthquake), A_{mmin} may be regarded as the minimum magnitude of the vibration we want our network to detect and A_{th} is the minimum vibration that can be detected by our system, then we can design r_s and R_{radio} to meet the requirements.

VIII. Results

The simulations evaluating the energy consumption per node and the internodal distance were performed in MATLAB and the results were compared with different schemes. The values of the different parameters used in the simulation are $e_t = 1024$ µJ/s, $e_r = 819.2$ µJ/s, $e_d = 2048$ µJ/m^2/s, $e_{id} = 409.6$ µJ/s, D = 6000 m, $T_{idlemin} = 30$ s. The values of K and T_d are 141 and 77.9 s respectively as found in section IV. However, in the plots shown in the subsequent figures, the value of K has been restricted to 139 instead of 141 for ease of visualization as for node index corresponding to 141, the internodal distance increases to approximately 1100 m. while the energy consumption rises to 0.095 J.

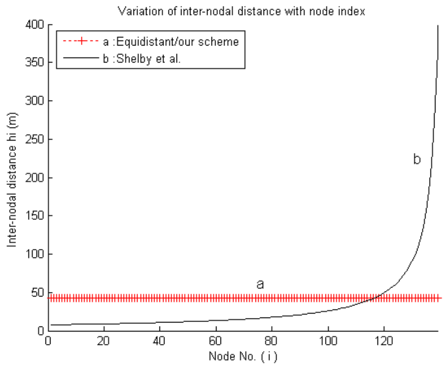

Fig. 4. Variation of inter-nodal distance (a) for our scheme/equidistant scheme of Shelby et al (b) for optimal scheme of Shelby et al.

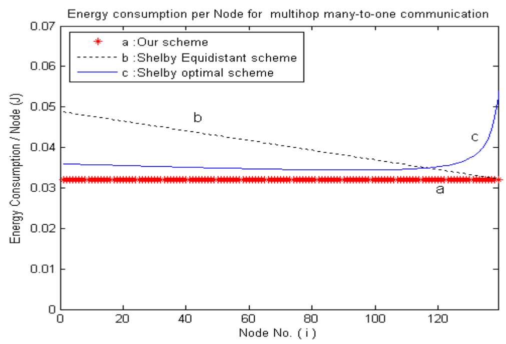

Fig. 5.Energy consumption per node (a) for our scheme (b) for equidistant scheme of Shelby et al. (c) for optimal scheme of Shelby et al

It is evident from Fig. 4. that in the scheme of optimal placement of nodes by Shelby et al. the spacing of the nodes increases drastically with distance beyond a certain node index and thus the radio range required to maintain connectivity in their scheme is far greater than ours. From Fig. 5., it can be inferred that the energy consumption per node in our scheme is far less than both the schemes proposed in [1]. Hence the claim that the network lifetime in our case will be greater is validated in Tab. 1.

Network Lifetime (in seconds)		
Shelby (optimal)	Shelby(equidistant)	Proposed scheme
58016	110710	168620

Tab. 1. Network Lifetime

IX. Conclusions

The scheduling scheme along with node deployment scheme performs more effectively than the network models taken into consideration in this paper. It has been shown in this paper that by assigning variable sleep time duration to the nodes, equal energy dissipation and thus 100% energy utilization can be achieved with equidistant node placement thereby keeping the radio range within feasible limits. This can be further extended to the analysis of two-dimensional fault tolerant wireless sensor networks and also for event driven sensor networks.

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