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Lifetime Maximization for WSNs

Mamoun H. M. and Enas M.
Faculty of Computers and information Sciences,
Mansoura University, Egypt

ABSTRACT

This paper presents a new sensor node deployment scheme to maximize sensor network lifetime. The key idea of the proposed scheme is to assign lower transmission power to a sensor node having higher traffic load. In this way, batteries of all nodes in a given area are discharged at the same current, thus they are depleted at the same time. Simulations have been conducted to evaluate the performance of the proposed scheme. Compared with peer work on heterogeneous deployment, the useable battery capacity by using the proposed scheme can be improved, and the operating time per sensor node can be enhanced. Furthermore, the proposed deployment scheme can reduce the number of sensor nodes required to cover the given area, leading to a significant reduction of deployment cost.

Keywords: *Wireless Sensor Networks, Lifetime Optimization, Energy Consumption*.

1. INTRODUCTION

A wireless sensor network (WSN) consists of sensor nodes capable of collecting information from the environment and communicating with each other via wireless transceivers. The collected data will be delivered to one or more *sinks*, generally via multi-hop communication. The sensor nodes are typically expected to operate with batteries and are often deployed to not-easily-accessible or hostile environment, sometimes in large quantities. It can be difficult or impossible to replace the batteries of the sensor nodes. On the other hand, the sink is typically rich in energy. Since the sensor energy is the most precious resource in the WSN, efficient utilization of the energy to prolong the network lifetime has been the focus of much of the research on the WSN.

Although the lifetime of the WSN can be defined in many ways, we adopt the definition that it is the time until the first node exhausts its energy, which is a widely used. Much work has been done during recent years to increase the lifetime of the WSN. Heterogeneous deployment schemes for sensor nodes have been proposed to balance the power consumption of each node in a given area. In [1], the optimal heterogeneous sensor deployment scheme was proposed to minimize the deployment cost in different communication modes. In that work, the cost of the cluster head was determined by the optimal number of cluster head nodes, the optimal mode of communication within a cluster, and the required battery energy consumption of both types of nodes. They did not consider the sensing coverage and communication mode. In [2], two kinds of deployment strategies were proposed. In the first approach, the highest battery resources are allocated to the ring where the highest energy drainage takes place. Each node in a ring has the same useable battery capacity. The second approach is based on using non-uniform node densities in different regions of the network. This method assumes a dense network and redundant nodes are deployed proportional to the energy consumptions in each region. Both methods balanced the energy consumption among sensor nodes and optimized the lifetime of wireless sensor networks.

Although the aforementioned schemes can balance the energy consumption among sensor nodes, they are all assumed that the battery of a sensor node has a fixed useable battery capacity. Recent studies reveal that useable battery capacity is time-varying, meaning that it decreases as the discharge current increases. The higher the discharge current, the lower the useable battery capacity is. This phenomenon is called battery current effect [3].

Therefore, in this paper, we study the relationship between node displacement and the current-rate effect. Since the sensor node deployment requires each node to know its battery status, we first develop a theoretical battery energy consumption model. Based on this model, the proposed deployment scheme considers the current effect by using different transmission power at sensor nodes. We assume an outdoor deployment of wireless sensors where line-of-sight connections are available. We divide the area of interest into concentric ring areas and deploy the nodes in these areas. So the shortest communication radius is assigned to the nearest ring to the information sink, which contains the nodes with the heaviest relay traffic. In this way, the nodes associated to deliver a packet from the source to the sink consume the same amount of battery energy, which, in the long run, could lead all nodes to exhaust their batteries about at the same time. Hence, the lifetime of the wireless sensor network is extended.

The remainder of the paper is structured as follows: In Section 2, we discuss the current effect and its relationship to the node deployment. We also study the discrete time battery model and provide a solution to measure useable battery capacity. Section 3 presents the problem statement and formulation. We optimize the lifetime of wireless sensor networks in Section 4. Section 5 discusses the simulation results and give concluding remarks in Section 6.

2. THE CURRENT EFFECT AND NODE DEPLOYMENT

In this section, we first discuss the battery model and the battery current effect, based on which we then introduce for a new battery-driven node deployment scheme.

2.1 The Battery Current Effect

Nickel-cadmium and Lithium-ion batteries are the most commonly-used batteries by wireless sensors and other out-door computing and communication devices. Usually a battery consists of cells arranged in series, in parallel, or a combination of both. Two electrodes, an anode and a cathode, are separated by the active material. When a cell is connected to a load, a reduction-oxidation reaction transfers the electrons from the anode to the cathode. Active species are consumed at the electrode surface and replenished by diffusion from the bulk of the electrolyte. A concentration gradient builds up across the electrolyte. The higher the load current is, the lower the concentration of the active species at the electrode surface. When this concentration is below a threshold, the voltage reaches cutoff value, and the electrochemical reaction cannot be sustained at the electrode surface. At this point, the charge that was unavailable due to the gradient remains unusable has its useable capacity reduced. Thus, the battery tends to provide more useable capacity at a low discharge current. [9] shows the nonlinear relationship between usable capacity and discharge current, where we can observe that the degradation of the deliverable capacity of a fully charged battery will change from the normalized usable capacity at the discharge current of $0{:}1C$ to about $0{:}9$ at the discharge current of $1C(41{:}3mA)$.

2.2 The Battery Model for Remaining Capacity Calculation

To capture the remaining capacity at the different currents, a battery model of sensor nodes is adopted in this work [4], which can be used to calculate the battery discharge loss due to the current effect. Given t_s as the beginning time of a load and t_e as the end time of the load, the battery energy which is dissipated $\alpha(I,t_s,t_e)$ of the battery during the load period $[t_s,t_e]$ is

$$\alpha(I,t_s,t_e)=IF(L,t_s,t_e,\beta^2) \qquad (1)$$

Where,

$$F(L,t_s,t_e,\beta^2)=t_s-t_e+2\sum_{m-1}^{\infty}\frac{e^{-\beta^2m^2t_s}-e^{-\beta^2m^2t_e}}{\beta^2m^2}$$

(2)

In this equation, α is the consumed capacity of the battery during the load period $[t_s,t_e]$, and is expressed in coulombs. The consumed capacity α is determined by two terms. The first term $I(t_s-t_e)$ is the consumed capacity by the load I.

The second term $2\sum_{m-1}^{\infty}\frac{e^{-\beta^2m^2t_s}-e^{-\beta^2m^2t_e}}{\beta^2m^2}$ is the amount of discharging loss due to the current effect. It can be observed that the discharge loss increases as the discharge current increases. β^2 is the constant related to the diffusion rate within each cell and captures the nonlinear current effect of a cell. The larger the β^2, the faster the battery diffusion rate is, hence the less the discharging loss. L is the total operating time of the battery. m is a factor from 1 to ∞.

As can be observed, useable battery capacity deceases as the discharge current increases. Given β^2 and the operating times t_s and t_e, we can calculate the available battery capacity at different loads. Then, we will use this battery model to study the deployment of the sensor nodes in a given wireless sensor network

3. NETWORK MODEL AND PROBLEM STATEMENT

3.1 Problem Statement

We assume a given area to be covered by wire-less sensor nodes, each of which will collect data periodically. Then, lifetime optimization of the wireless sensor network is to assign the different transmission power of nodes to balance their battery usage to avoid ”holes” in the network coverage. Thus, the goal of this paper is to decide the communication radius of each node. By using the optimal deployment, the lifetime of a sensor network is maximized while coverage and connection criteria is satisfied.

We utilize the concentric ring deployment scheme for wireless sensor networks as shown in Figure 2. Within each ring, the sensor nodes are uniformly distributed and have the identical communication range which can be controlled by the power manage module. We should decide the number as well as the communication range of all nodes in each ring, where the communication range is equal to the width of the corresponding ring. By using the optimal node communication range, the battery consumption of all nodes of the wireless sensor network is balanced and minimized. As a result, the lifetime of the wireless sensor network is prolonged, while the coverage and connection criteria can also be satisfied.

3.2 Network Lifetime

For most remote sensing applications, the main function of the wireless sensor network is to collect data. Therefore, the lifetime of a wireless sensor network is mainly determined by the last active node in the innermost ring.

3.3 Sensing Model

For a wireless sensor network to operate successfully, the sensor nodes must maintain both sensing coverage and net-work connectivity. Both of them directly determine the quality of a sensor network. For data collection, an important problem is how well a give area can be monitored to catch all the events by the wireless sensor network, which is often related to the quality of service, and known as sensing coverage [5], [6]. The sensing coverage is subject to a wide range of interpretations due to a large variety of sensors and applications. The goal is to have each location in the physical space of interest within the sensing range of at least on sensor.

To operate successfully, a wireless sensor network must also provide satisfactory connectivity so that all nodes can be used for data-gathering. Connectivity affects the robustness and achievable throughput of the communication link in a wireless sensor network. For an asymptotically connected network, the nodes are placed independently in a unit-area circle. According to [7], [8], the lower bound for the probability of connectivity P_r of nodes to cover a circle area with communication radius R is

$$P_r \leq 1 - Ne^{-N\pi R^2} \tag{3}$$

To satisfy a prescribed area coverage with a probability of at least $1-\sigma$, sensing model in equation (3) can be solved to determine the minimum number of nodes [8] necessary to cover circle and obtain a connected network

$$1-\sigma \leq 1 - Ne^{-N\pi R^2} \tag{4}$$

After scaling all distances by a communication range *r*, the equation (4) can be rewritten as [8]

$$\frac{N}{\log\left(\frac{N}{\sigma}\right)} \geq \frac{R^2}{r^2} \tag{5}$$

Thus, the relationship between the minimum number of nodes needed to cover area *A* of Fig. 2 and the communication range of each node can be denoted as [8]:

$$\frac{N_2}{\log(\frac{N_2}{\sigma})} \geq \frac{R_2{}^2 - R_1{}^2}{(R_2 - R_1)^2} \tag{6}$$

3.4 Concentric Ring Array

We propose to deploy nodes in a concentric ring array. The array consists of *M* rings. The numbering of the ring states from the innermost one so that the innermost ring is called 1st ring and the outermost ring is the *M*th ring. The mth; *m*= 0,*1, …,M* ring has N_m equally spaced array nodes and its radius is noted by R_m, where *m* = 0 denotes the sink. The number of nodes [8] which reside outside ring *m* is

$$K_m = \sum_{i=m+1}^{M} N_i \tag{7}$$

Thus, the average number of packet a_m [8] that a typical node in ring *m* has to relay is

$$a_m = \frac{\sum_{i=m+1}^{M} N_i}{N_m} \tag{8}$$

3.5 Energy Consumption

Assuming the energy consumed by a transceiver to transmit *k* bits packet over distance *d* is consumed by $k\left(\psi + \rho d^{\eta}\right)$, where ψ is the amount of energy consumed by the transmitter, and ρd^{η} is the amount of energy spent in RF amplifier. η is propagation loss exponent, which is dependent on the surrounding environment. Its value for free space is 2. For the receiving packet, only the receiver is involved, the energy consumed by receiving the packet is $k\Psi$. Consequently, the energy for relaying the packet over distance d is $k\left(2\psi + \rho d^{\eta}\right)$. The total energy consumed at the mth ring during one periodic data collection cycle [9] is

$$\begin{aligned} P_m &= k\left[\left(\psi + \rho d_m{}^{\eta}\right) + \left(2\psi + \rho d_m{}^{\eta}\right)a_m\right] \\ &= k\left[\left(\psi + \rho(R_{m+1} - R_m)^{\eta}\right) + \left(2\psi + \rho(R_{m+1} - R_m)^{\eta}\right)a_m\right] \end{aligned} \tag{9}$$

Usually, to provide a specific supply voltage *V* for a sensing device, a DC-DC converter is used. We assume the efficiency of the DC-DC converter is Á, and then the current I_m to power a node in m^{th} ring is:

$$I_m = \frac{P_m}{\phi V} \qquad (10)$$

4. LIFETIME OPTIMIZATION

We can observe from equation (10) that When a ring is closer to the sink, it will have a higher number of the packets. Therefore a heterogeneous topology with different communication range of nodes can balance and reduce the power consumption and prolong the lifetime of the network. If the full capacities of all batteries are C_0 and the capacity losses in each ring is denoted as $C_1; C_2; :::; C_M$, whose values can be obtained via the equation (3), the capacity loss for the m^{th} ring is

$$C_m = 2I_m \sum_{m-1}^{\infty} \frac{e^{-\beta^2 m^2 t_s} - e^{-\beta^2 m^2 t_e}}{\beta^2 m^2} \qquad (11)$$

the usable capacity ξ_m is

$$\xi_m = C_0 - C_m \qquad (12)$$

Therefore, each node has an average lifetime as follows

$$L_m = \frac{\xi_m}{k\left[\left(\psi + \rho\left(R_{m+1} - R_m\right)^{\eta}\right) + \left(2\psi + \rho\left(R_{m+1} - R_m\right)^{\eta}\right)a_m\right]}$$

m=1,2, …,M-1

$$L_M = \frac{\xi_m}{k\left(\psi + \rho\left(R_M - R_{M-1}\right)^{\eta}\right)} \qquad (13)$$

To prolong the lifetime of the wireless sensor network, the average lifetime of nodes should be equal to each other:

$$L_1 = L_2 = ... = L_M = L \qquad (14)$$

Thus, the problem is to determine the number of nodes N_m and the communication range R_m for maximum attainable lifetime, which can be formulated as follows

Maximize $L = Max\left(L_i\right)$ (15)

Subject to:

$$\frac{N_m}{\log\left(\frac{N_m}{\sigma}\right)} \geq \frac{R_m{}^2 - R_{m-1}{}^2}{\left(R_m - R_{m-1}\right)^2}$$

$$L_1 = L_2 = ... = L_M = L \qquad (16)$$

Thus, the formulated problem can be solved as a constraint nonlinear programming problem. The Lagrange relaxation can convert it into a equivalent unconstraint nonlinear programming

$$L(R, N, \lambda) = L_1 + \sum_{j=1}^{2M} \lambda_j \varphi_j (R, N) \qquad (17)$$

Where, the λ_1 , λ_2 , …., λ_{2M} is the undetermined Lagrange multipliers, φ_j is the equation constructed as

$$\varphi_j = \frac{N_j}{\log\left(N_j / \sigma\right)} - \frac{R_j{}^2 - R_{j-1}{}^2}{\left(R_j - R_{j-1}\right)^2}$$

$$\varphi_{j+M} = \frac{\xi_j}{k\left[\left(\psi + \rho\left(R_{j+1} - R_j\right)^{\eta}\right) + \left(2\psi + \rho\left(R_{j+1} - R_j\right)^{\eta}\right)aj\right]}$$

$$- \frac{\xi_j}{k\left[\left(\psi + \rho\left(R_{j+1} - R_j\right)^{\eta}\right) + \left(2\psi + \rho\left(R_{j+1} - R_j\right)^{\eta}\right)a_{j+1}\right]}$$

j=0,1,……,M-1

$$\varphi_{2M} = \frac{\xi_{2M}}{k\left(\psi + \rho\left(R_{2M} - R_{2M-1}\right)^{\eta}\right)} \qquad (18)$$

The values of λ_1, λ_2, …., λ_{2M} and maximum lifetime L can be obtained by the approach proposed in [9].

5. SIMULATION RESULTS

We describe the simulation setup parameters and then discuss the simulation results. In order to compare with the peer work, we adopt the same parameter set of the communication model as used in the simulation as used in [9], [10], which are shown in Table 1. We consider a circular shaped area with 500*m* radius, and then divide the area into 5 rings.

Table 1: Simulation Parameters

	Parameter Name	Value
R	coverage radius	500m
k	packet length	4200bits
ψ	energy of the radio electronics	50nJ/bit
ρ	energy of the power amplifier	0.0013pJ/bit/m4
η	path loss exponent	4
σ	connectivity bound	0.01
ϕ	the efficiency of the DC-DC	0.95

We simulated the performance of the proposed scheme as well as the scheme in peer work [8] The deployment scheme presented in [9] has no consideration of battery current effect and assume each node has the same communication radius, Therefore, all rings are evenly spaced, and the width of each ring is 100*m*. The total number of the nodes from the 1st to the 5th ring, assigned according to [8], are 294, 288, 252, 186, and 81 respectively.

For the proposed scheme, nonlinear battery current effect and variable communication radius are considered. The number of nodes in each ring and the width of ring (communication radius) are calculated via the equation (15). Results are summarized in

Table 2 which shows, the communication range of nodes in each ring increases from the innermost ring to the outermost ring. Thus, the energy consumption of the nodes in the vicinity of the information sink is reduced, and the energy consumption of the node far from the sink is relatively increased, and thus energy consumption of all nodes is balanced across the entire network.

Table 2: The Number of Nodes and the Communication Range

Ring No.	Communication radius (m)	No. of nodes
1	97.4705	27
2	97.7580	35
3	101.1695	46
4	107.0532	60
5	114.2108	76

We also adopt the Bellcore PLION battery cell [10] to power the wireless sensor nodes, which has 3:7*V* nominal voltage, 3 volt cutoff voltage, and (1C) battery capacity. The data of useable capacity vs. time can be obtained by the battery simulation software DUALFOIL program [11], which is a low-level battery simulator. All parameters of Bellcore PLION are setup according to [11].

Table 3 shows that the total number of nodes occupied each ring in both cases (the proposed scheme and heterogeneous deployment scheme).

Table 3: Total Number of Nodes Versus the Ring Number in Both Schemes

Ring No.	Total Number of Nodes	
	Traditional Scheme	Proposed Scheme
1	294	27
2	288	35
3	252	46
4	186	60
5	81	76

It is noticed from Table 3 that: For the existing heterogeneous deployment scheme, the density and the total number of nodes in the innermost ring are assigned a high value to balance the energy consumption for receiving and transmitting packets. For the proposed scheme, the total of number of nodes in each ring is about proportional to the communication radius of nodes in the corresponding ring, which provides an approximately uniform node density and allows uniform precise and fine-grained spatial information. Furthermore, the total number of nodes for the wireless sensor network with the existing heterogeneous deployment scheme is 1101, compared with 244 in the proposed scheme. Obviously, the proposed deployment scheme reduces the number of sensor nodes required to cover a given area, leading to a significant reduction of cost.

Figure 1 shows that the usable capacity comparison of both schemes. It is noticed that, the nodes in the proposed scheme have the same normalized full capacities, whose values are assumed as 1. The normalized full capacity of the first ring and second ring in the existing heterogeneous deployment scheme is 0:7895 and 0:9810, respectively. Thus, for the existing heterogeneous deployment scheme, only 78:95% of the battery capacity has been used. The operating time of the battery of nodes in the first ring and the second ring with the existing heterogeneous deployment scheme is 55:01 minutes and 247.43 minutes, respectively. The battery operation time of the proposed scheme is 558:90 minutes. Compared to the existing heterogeneous deployment scheme, the network lifetime of each node in the proposed scheme is improved about 20:95%, and the useable battery capacity is balanced and improved about 26:67%. Both are them are attributed to the reduced transmission power at the nodes in the innermost ring.

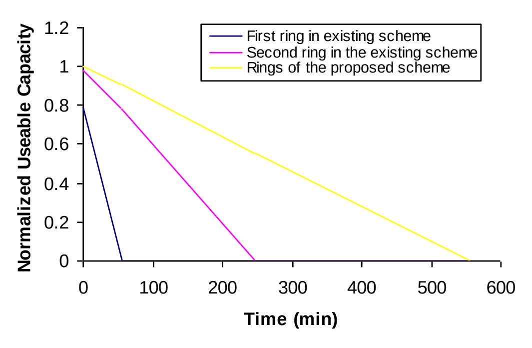

Figure 1: Useable Capacity Comparison of Both Schemes

6. CONCLUSION

In this paper, we have proposed a node deployment scheme for the wireless sensor network with consideration for the current effect. Based on the battery model, we presented a novel approach by assigning different communication radius to the nodes in a given wireless sensor network. Thus, the energy consumption of the nodes across the entire network is balanced, and thus the network lifetime is maximized. Meanwhile, the battery capacity is also fully utilized by balancing the load. Compared with the existing heterogeneous deployment scheme, the usable battery capacity of the proposed scheme is improved by 26.67%. Consequently, the lifetime of each node is extended by 20.95% Furthermore, the proposed scheme reduces the number of the nodes for covering a given area, implying a significant cost reduction.

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