Abstract—One of the design challenges of wireless sensor networks is the tradeoff between network operation time and network coverage. Recent studies reveal that the useable battery capacity drops faster at a higher discharge current in a nonlinear fashion. To take advantage of this battery current effect, in this paper we explore a new sensor node deployment scheme to prolong the entire sensor network lifetime as well as each individual sensor node. The key idea of the proposed scheme is to assign a sensor node having higher traffic load to adopt lower transmission power level. 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. Extensive simulations have conducted to evaluate the performance of the proposed sensor node deployment scheme. Compared with peer work on heterogeneous deployment, the useable battery capacity by using the proposed scheme can be improved by 26.67%, and the operating time per sensor node can be enhanced by 20.95%. 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.

I. INTRODUCTION

Wireless sensor networks consist of a large number of low cost devices to gather information from various kinds of remote sensing applications. In wireless sensor networks, data of interest need to be collected by each sensor node and then be transmitted to the information sink by using multi-hop relay via intermediate nodes. Therefore, the sensor nodes closer to the sink usually suffer a heavier data traffic and run out of battery quickly. When these intermediate nodes deplete their batteries, collected data cannot be transmitted back to the sink, resulting in network operation failure. Unfortunately, due to the large quantity of the sensor nodes, charging or replacing batteries of sensor nodes is not feasible. Therefore, a sensor node deployment is a very critical issue towards to the sensor network lifetime.

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], the heterogeneous deployment scheme of sensor nodes with different processing and communications capabilities was studied, and the simulation results showed that using an optimal mixture of many inexpensive, less powerful sensor nodes and some expensive, powerful sensor nodes can significantly extend the network lifetime. In [3], two kinds of deployment strategies were proposed. In the first approach, the highest battery resource is allocated to the ring where the highest energy drainage takes place. Each node on 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 [4]. 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 in this work. Based on this model, the proposed deployment scheme considers the current effect by using different transmission power level at sensor nodes.

Without losing generality, we assume an outdoor deployment of wireless sensors where line-of-sight connections are available. This assumption is valid in many application scenarios such as precision agriculture and environmental monitoring. Thus, the transmission power is directly determined by the communication radius. In this work, we divide the area of interest into concentric ring belts and deploy the nodes in these belts. Thus, 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 at the same time. Hence, the lifetime of the wireless sensor network can be prolonged.
Simulations have conducted to evaluate the performance of the proposed node deployment scheme. Compare with the existing deployment scheme where battery current effect is not considered, the proposed node deployment scheme can reduce the energy consumption of nodes near the sink. The battery utilization is improved by about 26.67%, and the lifetime of each node is enhanced by up to 20.95%. Meanwhile, the number of nodes in the proposed topology is reduced due to its even density deployment, and thus the cost of the proposed topology is significantly reduced too. The rest of the paper is organized as follows. In Section II, we discuss the current effect. We also study the discrete time battery model and provide a solution to measure usable battery capacity. In Section III, we present problem statement and a network model. We optimize the lifetime of wireless sensor networks based on the current effect in Section IV. We discuss the simulation results in Section V and give concluding remarks in Section VI.

II. CURRENT EFFECT AND BATTERY MODEL

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

A. Battery Current Effect

Nickel-cadmium and Lithium-ion batteries are the most commonly-used batteries by wireless sensors and other outdoor 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 electrochemical reaction cannot be sustained at the electrode surface. At this point, the charge is unavailable due to the gradient remaining unusable, and its usable capacity is exhausted. Thus, the battery tends to provide more usable capacity at a low discharge current. Figure 1 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).

B. 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 [5], 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:

\[
\alpha(I, t_s, t_e) = IF(L, t_s, t_e, \beta^2)
\]

Where,

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

In this equation, \( \alpha \) is the consumed capacity of the battery during the load period \([t_s, t_e]\), and is expressed in coulombs. The consumed capacity \( \alpha \) is determined by two terms. The first term \( I(t_s - t_e) \) is the consumed capacity by the load \( I \). The second term \( 2I \sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 (L-t_s)} - e^{-\beta^2 m^2 (L-t_e)}}{\beta^2 m^2} \) is the amount of discharge loss due to the current effect. It can be observed that the discharge loss increases as the discharge current increases. \( \beta^2 \) is the constant related to the diffusion rate within each cell and captures the nonlinear current effect of a cell. The larger the \( \beta^2 \), the faster the battery diffusion rate is and vice versa. \( L \) is the total operating time of the battery. \( m \) is a factor from 1 to \( \infty \) [5].

As can be observed, usable battery capacity deceases as the discharge current increases. Given \( \beta^2 \) 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.

III. PROBLEM STATEMENT AND NETWORK MODEL

A. Problem Statement

In this work, we assume a given area covered by wireless sensor nodes, each of which will collect data periodically. Then, the lifetime optimization of wireless sensor network...
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 $N$ nodes are placed independently in a unit-area circle. According to [3], [8], the lower bound for the probability ($P_c$) of connectivity of nodes to cover a circle area with communication radius $R$ is:

$$P_c(\text{The circle is connected}) \leq 1 - Ne^{-\pi R^2}$$  \hspace{1cm} (2)

To satisfy a prescribed area coverage with a probability of at least $1-\sigma$, sensing model in Eq. (2) can be solved to determine the minimum number of nodes $[3]$ necessary to cover circle and obtain a connected network:

$$1 - Ne^{-\pi R^2} \geq 1 - \sigma$$  \hspace{1cm} (3)

After scaling the distance by a communication range $r$, the Eq. (3) can be rewritten as [3]:

$$\frac{N}{\log(N/\sigma)} \geq \frac{R^2}{r^2}$$  \hspace{1cm} (4)

Thus, the relationship between the minimum number $(N_2)$ of nodes needed to cover area $A (R_1 < r < R_2)$ as shown in Fig. 2 and the communication range of each node can be denoted as [3]:

$$\frac{N_2}{\log(N_2/\sigma)} \geq \frac{R_2^2 - R_1^2}{(R_2 - R_1)^2}$$  \hspace{1cm} (5)

D. Concentric Ring Array

We propose to deploy nodes in a concentric ring array as shown in Fig. 2. The array consists of $M$ rings. The numbering of the ring states from the innermost so that the innermost ring is numbered $1^{st}$ ring and the outermost ring is the $M^{th}$ ring. The $m^{th}$ ring, $m = 0, 1, ..., M$, 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 [3] which reside outside ring $m$ is:

$$K_m = \sum_{i=m+1}^{M} N_i$$  \hspace{1cm} (6)

Thus, the average number of packet $a_m$ [3] that a typical node in ring $m$ has to relay is:

$$a_m = \frac{\sum_{i=m+1}^{M} N_i}{N_m}.$$  \hspace{1cm} (7)

E. Energy Consumption

Assuming the energy consumed by a transceiver to transmit a $k$ bits packet over distance $d$ is $k(\psi + \rho d^\eta)$, where $\psi$ is the amount of energy consumed by the transmitter, and $\rho d^\eta$ is the amount of energy spent in RF amplifier. $\eta$ is propagation loss exponent, which is dependent on the surrounding environment. For free space, it is 2. For receiving the packet, only the receiver is involved, so the energy consumed by receiving a packet is $k\psi$. Consequently, the energy for relaying the packet
over distance $d$ is $k(2\psi + \rho d^n)$. The total energy consumed at the $m^{th}$ ring during one periodic data collection cycle [3] is:

$$P_m = k[(\psi + \rho d^n_m) + (2\psi + \rho d^n_n)a_m]$$

$$= k[(\psi + \rho(R_{m+1} - R_m)^n) + (2\psi + \rho(R_{m+1} - R_m)^n)a_m] \tag{8}$$

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 $\phi$, and then the current $I_m$ to power a node in $m^{th}$ ring is:

$$I_m = \frac{P_m}{\phi V} = k[(\psi + \rho d^n) + (2\psi + \rho d^n_n)a_m] \tag{9}$$

### IV. Lifetime Optimization Using Heterogeneous Deployment Scheme Based on the Battery Current Effect

We can observe from Eq. (9) that when a ring is closer to the sink, it will have a higher traffic load. Therefore, a nonuniform topology with different communication ranges can balance and reduce the power consumption, and thus prolonging the lifetime of a network. If the full capacity of all batteries are $C_0$ and the capacity loss of nodes from the innermost ring to the outmost ring are denoted as $C_1, C_2, ..., C_M$, whose values can be obtained via the Eq. (2), for the $m^{th}$ ring, which is:

$$C_m = 2I_m \int_{m-1}^{\infty} e^{-\beta^2 m^2}(L_{m-1} - t_s) - e^{-\beta^2 m^2}(L_{m-1} - t_s) \frac{d t}{\beta^2 m^2} \tag{10}$$

Then, the useable capacity $\zeta_m$ is:

$$\zeta_m = C_0 - C_m \tag{11}$$

Therefore, each node has an average lifetime as follows:

$$L_m = \frac{\phi V \zeta_m}{k[(\psi + \rho(R_{m+1} - R_m)^n) + (2\psi + \rho(R_{m+1} - R_m)^n)a_m]} \tag{12}$$

$$L_M = \frac{\phi V \zeta_M}{k(\psi + \rho(R_M - R_{M-1})^n)} \tag{13}$$

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

$$\frac{\phi V \zeta_1}{k[(\psi + \rho(R_2 - R_1)^n) + (2\psi + \rho(R_2 - R_1)^n)a_1]} = \frac{\phi V \zeta_2}{k[(\psi + \rho(R_3 - R_2)^n) + (2\psi + \rho(R_3 - R_2)^n)a_2]} = \cdots \tag{14}$$

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 $L = \text{Max} (L_i)$

Subject to:

$$N_m = \frac{R_m^2}{log(\frac{R_M}{R_{M-1}})} \geq \frac{R_{m+1}^2 - R_m^2}{(R_m - R_{m-1})^2} \tag{15}$$

Where, $\lambda_1, \lambda_2, ..., \lambda_2M$ are the undetermined Lagrangian multipliers, $\varphi_j$ is the equation constructed as:

$$\varphi_j(R) = \frac{N_j}{log(\frac{R}{R_j-1})} - \frac{R_j^2 - R^2}{(R_j - R)^n} \varphi V \zeta_j \tag{16}$$

$$\varphi_j + M(R) = \frac{k[(\psi + \rho(R_{j+1} - R_j)^n) + (2\psi + \rho(R_{j+1} - R_j)^n)a_{j+1}]}{\phi V \zeta_j} - \frac{k[(\psi + \rho(R_{j+1} - R_j)^n) + (2\psi + \rho(R_{j+1} - R_j)^n)a_{j+1}]}{\phi V \zeta_j} \tag{17}$$

$$\varphi_2M(R) = \frac{\phi V \zeta_M}{k(\psi + \rho(R_{1+1} - R_1)^n)} \tag{18}$$

The values of $\lambda_1, \lambda_2, ..., \lambda_2M$ and maximum lifetime $L$ can be obtained by the approach proposed in [9].

### V. Simulation Results

In this section, we present the lifetime and cost evaluation of the proposed sensor node deployment scheme. We first 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 [3], [9], shown in Table I. We consider a circular shaped area with 500m radius, and then divide the area into 5 rings.

We simulated the performance of the proposed scheme as well as the scheme presented in peer work [3] The deployment scheme presented in [3] had no consideration of battery current effect and assume that each node has the same communication radius, Therefore, all rings are evenly spaced, and the width of each ring is 100m. The total number of the nodes from the 1st to the 5th ring, assigned according to [3], are 294, 288, 252, 186, and 81 respectively. In the proposed scheme, nonlinear battery current effect and variable communication radius are considered. The number of nodes in each ring and the width of each ring (communication radius) are calculated as shown in Table II, which are obtained via the Eq. (13). As shown in Table II, the communication range of nodes in each ring increases from the innermost ring to the outermost ring. Thus, the energy consumption of those nodes in the vicinity of

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ coverage radius</td>
<td>500m</td>
</tr>
<tr>
<td>$k$ packet length</td>
<td>4200bits</td>
</tr>
<tr>
<td>$\psi$ energy of the radio electronics</td>
<td>50mJ/bit</td>
</tr>
<tr>
<td>$\rho$ energy of the power amplifier</td>
<td>0.0013pJ/bit/m²</td>
</tr>
<tr>
<td>$\eta$ path loss exponent</td>
<td>4</td>
</tr>
<tr>
<td>$\sigma$ connectivity bound</td>
<td>0.01</td>
</tr>
<tr>
<td>$\phi$ the efficiency of the DC-DC</td>
<td>0.95</td>
</tr>
<tr>
<td>$V$ output voltage of the DC-DC</td>
<td>3volts</td>
</tr>
</tbody>
</table>
TABLE II
THE NUMBER OF NODES AND THE COMMUNICATION RANGE

<table>
<thead>
<tr>
<th>Ring No.</th>
<th>Communication radius (m)</th>
<th>No. of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>97.4705</td>
<td>27</td>
</tr>
<tr>
<td>2</td>
<td>97.7580</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>101.1695</td>
<td>46</td>
</tr>
<tr>
<td>4</td>
<td>107.0532</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>114.2108</td>
<td>76</td>
</tr>
</tbody>
</table>

Fig. 3. Useable capacity comparison of both schemes. Here, the existing scheme [3] is a heterogeneous deployment scheme without considerations of battery current effect and all nodes having the same communication radius. The proposed scheme is a new heterogeneous sensor node deployment scheme using nonlinear battery effects with different communication ranges.

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.

We also adopt the Bellcore PLION battery cell [10] to power the wireless sensor nodes, which has 3.7V nominal voltage, 3V cutoff voltage, and (1C = 41.3mAH) 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].

Figure 3 shows that the usable capacity comparison of both schemes. The curve in blue and the curve in black denote useable capacity vs. time of nodes of the first ring and the second ring, respectively, compared with the existing heterogeneous deployment scheme. The curve in red corresponds to useable capacity vs. time of nodes with the proposed scheme. All nodes in the proposed scheme have the same normalized full capacity set as 1. The normalized full capacity of the first ring and the 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 can be 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 with the existing heterogeneous deployment scheme, the network lifetime of each node in the proposed scheme has been improved about 20.95%, and the useable battery capacity has been balanced and improved about 26.67%. Both are attributed to the reduction of transmission power used by the nodes in the innermost ring.

Figure 4 shows that the comparison of the total number of node in each ring. The bar in blue denotes the total number of nodes in each ring with the existing heterogeneous deployment scheme. The bar in red corresponds to the total number of nodes in each ring by using the proposed scheme. For the existing heterogeneous deployment scheme, the density and the total number of nodes in the innermost ring are assigned to a larger value to balance the energy consumption used for receiving and transmitting packets. For the proposed scheme, the total 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 by adopting the existing heterogeneous deployment scheme is 1101, compared with 244 by using the proposed scheme. Therefore, the proposed deployment scheme significantly reduces the number of sensor nodes required to cover a given area, leading to great cost reduction.

VI. CONCLUSION

In this paper, we have proposed a node deployment scheme for wireless sensor networks with consideration of the current effect. Based on battery model, we have presented a novel approach by assigning different communication radii to nodes in a given network. Thus, the energy consumption of each
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 traffic load among nodes. Compared with the existing heterogeneous deployment scheme, the usable battery capacity offered by the proposed scheme is improved by 26.67%. Consequently, the lifetime of each node is extended by 20.95% Furthermore, the proposed scheme needs much less number of nodes for covering a given area, implying significant cost reduction.

REFERENCES


