A Preliminary Study on Lifetime Maximization in Clustered Wireless Sensor Networks with Energy Harvesting Nodes

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***Abstract*—Clustering is used extensively in wireless sensor networks to optimize lifetime. Within clustering, the optimization of cluster head (CH) location is critical since CHs consume energy faster and have greater influence on lifetime than non cluster head (NCH) sensors. Energy harvesting wireless sensor networks (EH-WSNs) use energy harvesting devices to harvest energy from environment. In contrast with the traditional battery powered wireless sensor networks, EH-WSNs have extended network lifetime substantially.**

In this paper, we present a single cluster algorithm for lifetime optimization in homogeneous wireless sensor networks with one solar powered sensor. The proposed method could determine the optimal CH location within a given network distribution. We include the solar powered sensor node as relay node for CH and determine the optimal position for it. We evaluate the performance of our method through theoretical analysis as well as simulation. We found through the use of our method, the overall network lifetime could be optimized.

I. INTRODUCTION

Wireless sensor networks (WSNs) are gaining wide applications and booming research interest in recent years [1]. A critical issue in WSNs is to achieve high energy efficiency since sensor nodes are typically powered by batteries with limited stored energy, which cannot be conveniently replaced or recharged. Various solutions have been proposed for prolonging the lifetime of WSNs, among which include solutions utilizing network clustering.

In a clustered WSN, sensor nodes are grouped into clusters. Each cluster typically comprises a single cluster head (CH) and the others are non-cluster heads (NCHs). NCHs communicate with the CH, which is then responsible for processing the data it receives (if applicable) and forwarding the information, either via a relay node or, directly to the base station (BS). In such networks, the energy consumption of NCHs is typically lower since they only need to communicate with CHs which are generally nearby. The energy consumption of CH, however, may be much higher since it needs to process and transmit the information for the whole cluster with the BS directly if no relay node is available. Since energy consumption for data transmission is largely decided by communication distance, finding the best CH location is of critical importance: a sub-optimal location may force the CH to communicate over a very long distance and consequently use up its stored energy quickly.

In parallel to the developments in network clustering techniques, an important recent progress in prolonging WSN lifetime is the utilization of energy harvesting (EH) to power wireless sensors [1]. EH sensor nodes can harvest energy, e.g., solar, kinetic, thermal energy etc, from the environment. They may have infinite lifetime due to the large number of recharge cycles made possible by energy storage devices such as super-capacitors. Due to the higher cost and other physical limitations of current EH sensor nodes, however, it is impractical to deploy a large-scale WSN composed only of EH sensor nodes in the near future. An arguably more practical approach may be to adopt EH sensor nodes sparsely in WSNs.

Hence, a natural approach for prolonging the lifetime of WSNs is to combine clustering and energy-harvesting technologies, or in other words, to intelligently utilize sparse EH sensor nodes in clustered WSNs. Since the energy harvesting rates of most EH devices are rather sensitive to the environment [2], it may not be practical to adopt an EH node as the CH in most cases. We investigate the case where an EH node serves as a relay node between a CH and BS (or the next relay node), so that CH can communicate with EH node over a shorter distance with a lower level of energy consumption, at least for a certain fraction of time.

As the first step towards a comprehensive study, in this paper, we study the simple case where there is only a single cluster and the locations of all the sensors are known. Our objective is to devise simple yet efficient algorithms for finding the best locations of CH and EH nodes so that the lifetime of the single cluster is maximized. Our preliminary study generates efficient algorithms which can be extended to handle more realistic scenarios of multi-cluster, decentralized networks, and provides useful benchmarks for future designs.

The rest of the paper is organized as follows: In Section II, we briefly describe related work in clustering and energy harvesting. In Section III, we propose algorithms to determine optimal positions of CH and EH nodes in a single-cluster network and prove their correctness. Extensive simulation results and discussions are provided in Section IV. Finally, Section V concludes the paper and provides directions for future research.

II. RELATED WORK

There exist many different definitions of network lifetime in WSNs [3], including the time until (i) the first node drains out of energy [4], (ii) a certain fraction of nodes die out [5], and (iii) a certain coverage or connectivity constraint in a certain region cannot be fulfilled. As the definition in [4] is popular in the literature, we adopt this definition in the paper.

Clustering technology for WSNs has been extensively studied [6], covering various aspects, including sensor design and testing, distributed/centralized clustering formation, wake-up scheme design and fault tolerance. Existing works on selecting the optimal CH location to optimize network lifetime [7], [8], [9] formulate the problem into Mixed Integer Nonlinear Programming (MINLP) problem and solve it using general solvers. In [7], the authors proposed an algorithm based on sequential location-allocation (SLA) decomposition scheme to minimize the communication power and achieve reliability for large-scale network and compared the results with those obtained by the MINLP solver. In [8], the author used MINLP solver to solve the micro-server deployment problem and energy allocation (MDEA) problem. Their results showed that the network lifetime could be increased by a factor of two or more compared to a non-clustered WSN. In [9], the author solved the optimization problem with capacity, cost, QoS and connectivity constraints using MINLP solver, and compared their results with augmenting and grid-based approach. As the MINLP solver is unsuitable for solving large-scale cases, we prefer to use a different approach in our work.

While there has been some study on clustering in WSNs with EH nodes [10], [11], these works mainly use the existing clustering algorithm for battery powered WSNs and modify the algorithm to suit EH-WSNs. To the best of our knowledge, there are no existing results for finding the best locations of CHs or EH nodes in clustered WSNs to maximize lifetime.

III. LIFETIME-OPTIMAL CH-EH NODE PLACEMENT FOR SINGLE CLUSTER

In this paper, we consider the deployment of N sensor nodes in a 2-D region, where nodes are stationary, homogeneous and location-aware. A base station (BS), assumed to have infinite energy, is deployed at (0,0). Amongst the N nodes, one node will be selected as the CH, which is assumed to be able to fuse information from all NCHs. We denote by NCH_f the NCH node that is furthest away from the CH. We assume an EH node that can harvest solar energy from the environment, and has an energy storage device. Our network model is depicted in Figure 1.

We assume the same energy model as defined in LEACH [12], where the radio dissipates E_{elec} per bit to operate the transmitter/receiver circuitry and E_{amp} per bit for the transmitter amplifier. Table I shows the notations used throughout the paper.

A. Procedure for Single Cluster Algorithm

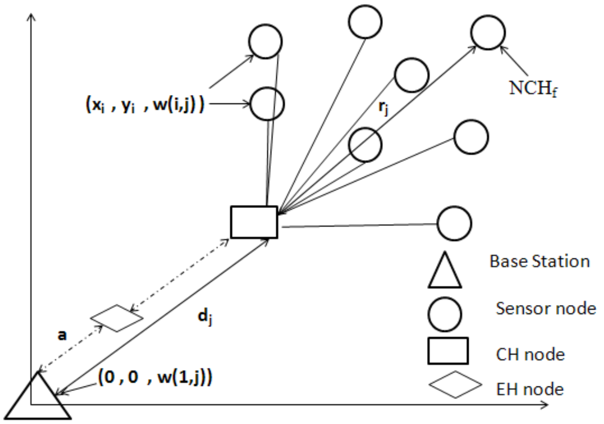


Fig. 1. Our proposed single cluster WSN model.

TABLE I
NOTATIONS USED THROUGHOUT THIS PAPER

k	data transmission rate in kbps
N	number of sensors in the network
i	1,2,..N, refers to the index of node
j	index of iteration
(x_i, y_i)	coordinates for node i
$w(i,j)$	weight assigned to node i at iteration j
d_j	distance between CH with base station at iteration j
r_j	distance between CH with NCH_f at iteration j
$\widehat{t}$	lifetime for CH
P	harvesting rate for EH node
t_{EH}	time duration when EH node works
P_{EH}	energy consumption rate for EH
P_{CH1}	energy consumption rate for CH when EH is not working
P_{CH2}	energy consumption rate for CH when EH is working
E	energy stored in battery for each sensor
a	distance between EH and BS

We assume a TDMA frame that comprises N slots: the N-1 NCH nodes will transmit to CH in the first N-1 slots while the CH node listens, and then the CH node will transmit in N^{th} slot to BS. Accordingly, the power required for CH and NCH_f at j^{th} iteration is shown below:

$$P_{CH} = E_{elec} * k * (N-1) + E_{elec} * k + E_{amp} * d_j^2 * k \quad (1)$$

$$P_{NCH_f} = E_{elec} * k + E_{amp} * r_j^2 * k \quad (2)$$

Intuitively, we know that NCH_f expends more energy than other NCH. From Figure 1 and Equation (1)-(2), if $d_j << r_j$, then P_{NCH_f} may be very high; on the other hand, if $d_j >> r_j$, P_{NCH_f} is reduced at the expense of P_{CH}. Therefore, our idea is that if we can position the CH such that both CH and NCH_f use up their energy at the same time, then the network lifetime will be maximized if this energy is minimized. Mathematically, this can be expressed as follows:

$$\min(P_{CH}, P_{NCH_f})$$

subject to $P_{CH} = P_{NCH_f}$. Since $P_{CH} > P_{NCH_f}$ for same d_j and r_j, intuitively, d_j should be slightly smaller than r_j to obtain equal P_{CH} and P_{NCH_f}.

This problem closely resembles the well-known weighted smallest circle problem, which is defined as follows [13]. Let n points, $p_i = (x_i, y_i)$, $i = 1, ..., n$ be given together with positive weights w_i $(i = 1, ..., n)$. For any point $p = (x, y)$, let $d(p, p_i)$ be the distance between p and p_i and

$$H(p) = \max_{1 \le i \le n} w_i d(p, p_i).$$

The weighted smallest circle problem is to find a point $p^* = (x^*, y^*)$ so as to minimize H.

Since $d_j < r_j$, we will assign BS with weight $w(1, j)$ larger than 1 and other NCHs with weight 1 at j^{th} iteration. By using weighted smallest circle algorithm, we will obtain values for r_j and d_j. We assume that the BS and NCH_f are critical points located on the boundary of a circle, i.e., $r_j = d_j * w(1, j)$. In order to suit our idea, we add another constraint Equation (1) = Equation (2). Then, the formula for BS weight in j^{th} iteration is derived as shown below:

$$E_{elec} * k * (N-1) + E_{elec} * k + E_{amp} * d_{j-1}^2 * k$$
$$= E_{elec} * k + E_{amp} * (d_{j-1} * w(1, j))^2 * k$$

$\Rightarrow$

$$w(1, j) = \sqrt{(E_{elec} * (N-1)/(E_{amp} * d_{j-1}^2) + 1} \tag{3}$$

Our proposed algorithm is shown in Algorithm 1.We prove that d_j, r_j, w_j will converge within finite steps. Here $w_j = w(1, j)$. The proof is shown below:

Algorithm 1 Single Cluster Algorithm

- **Initialization**
  Input set of sensor locations $A = (x_1, y_1), (x_2, y_2)...(x_N, y_N)$. Let $(x_1, y_1) = (0, 0)$ which represents the coordinate for the BS.
- **Step 1**
  $w(i, 1) = 1$, where $i = 1, 2, ..., N$, run the weighted smallest circle algorithm to find the center point of the circle, record the coordinate as (x_1^*, y_1^*), and record d_1 and r_1.
- **Step 2**
  Let $w(i, j) = 1$ for $i = 2, 3, ...N$. Let BS weight equal to $w(1, j)$ according to equation 3 for $j = 2, 3, ...$ Run the weighted smallest circle algorithm to find the center point for the j^{th} iteration, record the coordinate as (x_j^*, y_j^*), record d_j and r_j.
- **Step 3**
  Check if $|d_j - d_{j-1}| \le \epsilon$, if so, go to step 4, else, return to step 2.
- **Step 4**
  Now we have the optimal CH position denoted as (x^*, y^*), we select the sensor that is closest to this point as CH. Other sensors will remain as NCH node.

Lemma 1. *Given $w_{j+1} \ge w_j$, we have $r_{j+1} \ge r_j$.*

Proof: (Proof by contradiction) If given $w_{j+1} \ge w_j$, then we have $r_{j+1} < r_j$. Let $(\overline{x}_j, \overline{y}_j) = (x_{j+1}^*, y_{j+1}^*)$, and $\overline{r} = r_{j+1}$. we have a feasible solution for the j^{th} iteration. $r_j \le \overline{r} = r_{j+1}$ which causes a contradiction. Hence, the lemma is proved to be correct. ■

Theorem 1. *If $w_{j+1} \ge w_j$, then either the algorithm terminates, that is $r_{j+1} = r_j$, or $d_{j+1} \le d_j$.*

Proof: Let $(\overline{x}_{j+1}, \overline{y}_{j+1}) = (x_j^*, y_j^*)$ and

$$\overline{r} = \max\{w_{j+1} d_j, r_j\}$$

we have a feasible solution for the $(j+1)^{th}$ iteration where the center of the circle is at (x_j^*, y_j^*) and the radius is $\overline{r}$.

If $\overline{r} = r_j$, then $r_{j+1} \le \overline{r} = r_j$. From Lemma 1, $r_{j+1} = r_j$. The algorithm terminates.

If $\overline{r} = w_{j+1} d_j$, we have $w_{j+1} d_{j+1} \le r_{j+1} \le \overline{r} = w_{j+1} d_j$, hence $d_{j+1} \le d_j$ ■

Theorem 2. *d_j will converge within finite steps of j.*

Proof: From our equation 3, we have $w_2 > w_1$, so using the theorem, we have $d_2 \le d_1$, we find when d_j decreases, w_{j+1} will increase, hence, w_j is a monotonically increasing function. Therefore, d_j is a monotonically decreasing function with j. We know $d_j > 0$, so d_j is monotonic variable with lower bound, which means d_j will converge within finite steps. Similarly, since w_j, r_j are function of d_j, they will converge with finite steps. ■

B. Solar Powered Sensor as Relay Node

Let us denote by E the energy stored in the CH node at the end of N-1 slots, and by $\widehat{t}$ its lifetime, or the time from this instant until its energy is depleted. In this section, we will evaluate the placement of the CH as well as an EH node (see Figure 1) to optimize $\widehat{t}$.

Over the duration of $\widehat{t}$, the amount of energy that the EH node (assumed to have zero initial energy) can harvest is given by $P\widehat{t}$. Since it consumes energy at the rate of P_{EH}, it can remain active and relay data for the CH for a duration t_{EH}, where

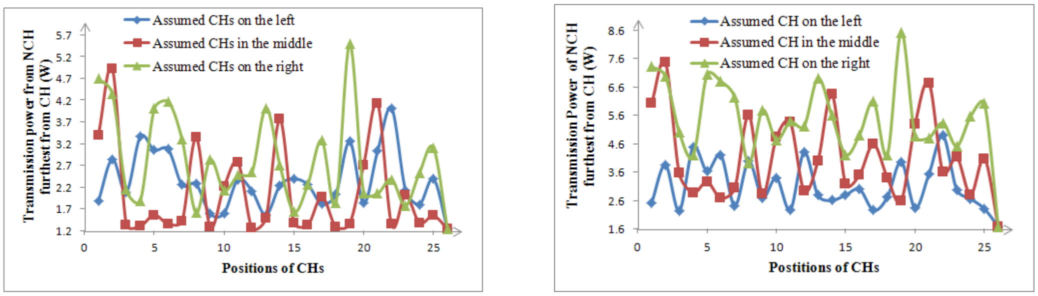
$$t_{EH} = \min\left(\frac{P\widehat{t}}{P_{EH}}, \frac{E}{P_{CH2}}\right),$$

where the latter term is the lifetime of the CH node when it transmits via the relay node.

During this period, the energy depleted in the CH node is given by $P_{CH2} t_{EH}$. Subsequently, the EH node is inactive, and the CH node transmits directly to the BS for a duration of $\frac{E - P_{CH2} t_{EH}}{P_{CH1}}$ until its energy is depleted. Accordingly, we obtain the expression for $\widehat{t}$ as:

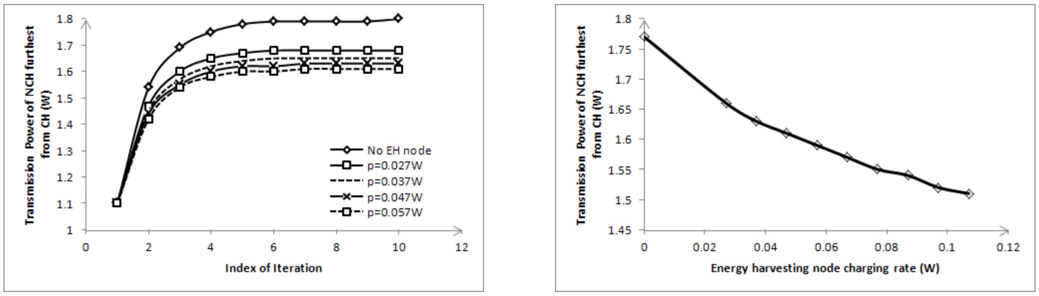
$$\widehat{t} = \begin{cases} \frac{P\widehat{t}}{P_{EH}} + \frac{EP_{EH} - P_{CH2} P\widehat{t}}{P_{CH1} P_{EH}}, & \widehat{t} < \frac{EP_{EH}}{PP_{CH2}}; \\ \frac{E}{P_{CH2}}, & \text{otherwise}; \end{cases} \tag{4}$$

where P_{CH1}, P_{CH2} and P_{EH} can be expressed in terms of d and a in a similar way as Equation (1).



(a) (b)

Fig. 2. Transmitting power of NCH_f for (a) Case I (b) Case II



(a) (b)

Fig. 3. (a) Rate of convergence of our proposed algorithm and (b) Effect of energy harvesting rate on the transmission power of NCH_f with the inclusion of one solar powered sensor node

Using Equation (4), we calculate the derivative $\frac{d\hat{t}}{da}$ in order to determine the optimal value for a. We find that when $a \leq a^*$, $\hat{t}$ is monotonically increasing with the increase of a, and when $a \geq a^*$, $\hat{t}$ is monotonically decreasing with the increase of a, where:

$$a^* = \sqrt{\frac{P - E_{elec} * k}{E_{amp} * k}}$$

Thus, a^* is the optimal value, and the corresponding maximum lifetime can be expressed as:

$$\hat{t}_{max} = \frac{E}{E_{elec} * k + E_{amp} * (d - a^*)^2}$$

Next, to determine the optimal CH position, we use the same approach as shown in Section III-A by letting $P_{CH} = P_{NCH_f}$, where

$$P_{CH} = P_{CH1} * \frac{\hat{t} - t_{EH}}{\hat{t}} + P_{CH2} * \frac{t_{EH}}{\hat{t}},$$

and P_{NCH_f} is same as shown in Equation (2). We apply Algorithm 1 to determine the optimal CH position; however, instead of using Equation (3), the weight for BS is shown below:

$$w(1,j) = \sqrt{E_{elec} * (n-1)/(E_{amp} * d_{j-1}^2) + \frac{(d_{j-1} - a^*)^2}{d_{j-1}^2}} \tag{5}$$

After the optimal CH position (x^*, y^*) is obtained, the optimal position for the EH node is then given by (a*$\sin \arctan(y^*/x^*)$, a*$\cos \arctan(y^*/x^*)$). The proof of convergence is the same as that shown in Section III-A.

IV. SIMULATION RESULTS

We validate our results through simulations for a 2-D network with BS deployed at (0,0) and $N = 100$ nodes randomly distributed over a 200m × 200m region, each with data transmission rate of 250 kbps per node. We first verify that our new algorithm could find best location of CH for maximizing the lifetime of a cluster. Next, we verify the case where we have a single EH node for relay. Finally, we show the increase of network lifetime after adding one EH sensor and observe the effect of harvesting rate on the overall network lifetime. We use simulations to quantitatively get the optimal CH positions.

A. *Verifying Best CH Location*

We condiser two square regions of network deployment, where the coordinates of the vertices are as follows: Case (I) (-100, -100), (-100, 100), (100, 100) and (100, -100); Case II (100, 100), (100, 300), (300, 300), (300, 100).

For each case, we evaluate the transmission power of NCH_f when the CH position is computed using Algorithm 1. To show that this solution is optimal, we carry out the corresponding evaluation when the CH is deployed randomly in 25 locations in three regions where the coordinates of the vertices are as follows: (i) Left (-200,-200), (-200,200), (-100,200), (-100,-200); (ii) Middle (-100,200), (-100,-200), (100,200), (100,-200) and (iii) Right (100,200), (100,-200), (200,200), (200,-200). The results are plotted in Figure 2a, where position 26 corresponds to that obtained with Algorithm 1. The deployment of assumed CH position strategy is similar in Figure 2b.

We plot the results in Figure 2 when CHs are in different locations and show that the transmission power of NCH_f is lowest for position 26, i.e., our results are indeed optimal. Since all the node has the same battery energy, the lifetime could be E/P_{NCH_f}, i.e., the network lifetime is maximized.

B. Inclusion of solar powered node

We then consider adding one solar powered sensor node into our network. The optimal CH location derived from our algorithm could be similarly verified as in Section IV-A. The algorithm after including one solar powered node is same with Algorithm 1 except for some changes on the BS weight as shown in Equation 5. We assume the sensors are distributed according to Case (II) in Section IV-A and show the effect of adding one solar powered node on the overall network lifetime.

In Figure 3, we show the effect of adding one sensor node on the overall network lifetime and the effect of changing energy harvesting rate on the overall network lifetime. According to previous literature [14], we assume the EH node charging rate, P, is around 37 mW for direct sunlight. In Figure 3a, four cases of P from 0.027W to 0.057W are compared including the case with no EH node. We show the effect of index of iteration on the results. Our algorithm could converge within 10 steps of iterations. After adding one solar power node, the maximal sensor transmission power is reduced, so that the lifetime is increased.

We show the effect of energy harvesting rate on the overall network lifetime in Figure 3b. We find that as P increases, the transmission power is reduced, which increases the network lifetime. We find that after adding one sensor node, the network lifetime is increased by 8.59% when P is 0.037W compared with the case without EH node (denoted by P=0).

V. CONCLUSION AND FUTURE WORK

In this paper, we propose a single cluster algorithm for selecting the optimal position of CH to maximize the lifetime of battery powered wireless sensor network. We then modify our algorithm to consider the effects of adding a solar powered sensor node as relay node between the BS and the CH. We verify that our new algorithm could find best location of CH for maximizing the lifetime of a cluster. We also show the improvement in network lifetime after adding one EH sensor and observe the effect of harvesting rate on the overall network lifetime. We find the network lifetime is increased by 8.59% compared with the case without EH node.

For future work, we plan to (i) extend our algorithm for multi-cluster network inclusion of solar powered nodes using our proposed single cluster algorithm; (ii) extend our work to take consideration with other WSN measuring metrics such as throughput and packet delivery ratio instead of lifetime; (iii) simulate and implement our algorithm with more realistic models. In the long term, we hope to implement and evaluate the proposed algorithm in an actual environment.

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