Distributed Relay Scheduling for Maximizing Lifetime in Clustered Wireless Sensor Networks

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Abstract—**Clustering and relaying techniques are important approaches towards mitigating the problem of finite network lifetime in wireless sensor networks. To this end, given a clustered wireless sensor network (WSN) (with defined cluster heads and their associated clusters) and a given relay node placement, we present a distributed service allocation algorithm for the relay node for maximizing network lifetime. We evaluate the performance of our method through theoretical analysis as well as simulations, and demonstrate the superior performance of our proposed method compared to a greedy periodic approach.**

I. INTRODUCTION

Wireless sensor networks (WSNs) are gaining booming interest in recent years [1]. Potential applications for WSNs include health-care, structure health monitoring, auto-mobile, smart phone etc. One of the critical limitations of WSNs is finite network lifetime as it is often difficult or inconvenient to replace/recharge batteries in battery-powered sensor nodes. Therefore, it is necessary to improve the energy efficiency of WSNs to maximize network lifetime. Approaches in the literature to maximize network lifetime include clustering and deployment of dedicated relay nodes.

We consider a clustered WSN as comprising four types of entities: (i) a base station (BS) which is the data sink, and is usually assumed to have infinite energy (i.e., mains powered); (ii) non cluster head (NCH) sensor nodes; (iii) cluster head (CH) sensor nodes; and (iv) relay nodes. NCHs sense information from the environment, and forward the data to their respective CHs. CHs sense data from the environment, receive and aggregate data from NCH nodes, and forward the data to the BS, either directly or through relay nodes. There are three key phases involved in maximizing the lifetime of such a network: (i) Cluster head selection; (ii) Cluster formation and transmission scheduling; and (iii) relay node placement and scheduling.

CHs consume more energy than NCHs due to the additional energy consumed for receiving and aggregating. Moreover, CHs usually transmit over a longer distance to the relay nodes compared to the distances between NCHs and CHs. Therefore, proper selection of CHs is of utmost importance for prolonging the network lifetime, as a poor choice of CHs may force either NCHs or CHs to use up their energy quickly. After CHs are selected, NCHs select the appropriate clusters to join in order to maximize their lifetime. However, NCHs do not always join the closest CHs since a large cluster size may force CHs to die quickly. Therefore, cluster formation has to considered jointly with cluster head selection.

Since transmission power is largely dependent on the transmission distance, dedicated relay nodes serve to reduce the transmission power of CHs and hence maximize their lifetime. Therefore, it is important to determine the time each relay node spends on each CH. The longer the time each relay node spends on a CH, the larger the energy saving the CH could have, but the lower the amount of time the relay node has to serve other CHs.

In our previous works [2], we adopted a centralized approach to solve the above problem, where we considered nodes powered by ambient energy harvesting as dedicated relay nodes for cluster heads, and proposed joint clustering and relay node placement algorithms for network lifetime maximization. We demonstrated the polynomial time convergence of our proposed algorithms, as well as their near optimality (compared to brute force approaches) through extension simulations.

In this paper, we study a related problem that differs from our previous work in the following ways: we assume (i) a single battery-powered relay node that serves multiple CHs instead of dedicated relay nodes powered by ambient energy harvesting; and (ii) the location of each node is unaware to BS. Given that cluster head selection and cluster formation have been accomplished, our objective is to device a simple yet efficient distributed algorithm to optimally allocate the relay node to serve the CHs to maximize network lifetime. The proposed algorithm can be extended to the case where the relay nodes are powered by ambient energy harvesting, and serves as a building block towards a distributed solution for network clustering.

We organize the rest of the paper as follows: In Section II, we briefly describe related work in network clustering in WSNs. In Section III, we propose algorithms to determine the optimal service time for each CH by the relay node in a multiple-cluster network and prove their correctness. Extensive simulation results to validate the optimality of the proposed algorithm and discussions are provided in Section IV. Finally, Section V concludes the paper and provides directions for future research.

II. RELATED WORK

Clustering technology for WSNs has been extensively surveyed in [3], and existing work can be broadly classified under CH selection [4], cluster formation [5] and scheduling of relay nodes [6]. Centralized methods, for example, [2], [7], [8], [9], typically require knowledge of the nodes' location and involve solving a global optimization problem. On the other hand, distributed methods, for example, [4], [5], make decisions based on local information with limited information exchanges between neighboring nodes. Most existing works aim to minimize the energy consumption of CHs [7], [8], [9] or the overall energy consumption [4], [5] by solving a minimization problem. Our approach [2] focuses on maximizing the network lifetime by solving a min-max problem, because the network lifetime is typically determined (or is strongly affected) by a certain number of nodes, i.e., bottleneck nodes, which are usually, but not always, CHs.

Many different network lifetime definitions exist in WSNs [10], and they include the time until (i) a certain percentage of nodes dies; or (ii) a certain coverage or connectivity cannot be fulfilled. We adopt the first definition, specifically, we use the time until the first node dies as the network lifetime definition [11].

III. LIFETIME-OPTIMAL RELAY NODE SCHEDULING FOR MULTI-CLUSTERED WSN

A. System Model

In this paper, we consider a homogeneous and fixed clustered WSN deployment in a 2-D region that comprises a mains-powered base station (BS) located at (0,0), N_c CH nodes and N_s-N_c NCH nodes deployed randomly, and a relay node deployed between the sensor nodes and the BS. We assume that the CH nodes have been selected, and clusters have been formed. Our network model is depicted in Figure 1. We also assume that the network is sufficiently far away from the BS such that the network lifetime is given by the time till the first CH node runs out of energy.

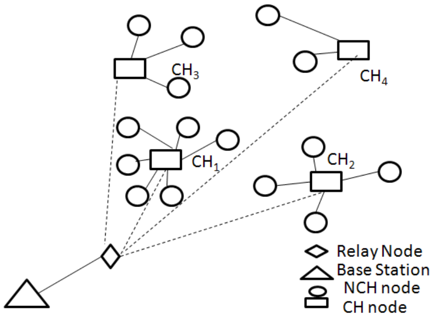

Fig. 1. Our proposed clustered WSN model.

We assume a TDMA frame (also denoted as a round) that comprises N_s slots: the $N_s - N_c$ NCH nodes will transmit to their corresponding CHs in the first $N_s - N_c$ slots while the CHs listens; the CHs will then transmit in the remaining N_c slots to BS, either directly or through the relay node. Through some message exchanges between the CHs and relay nodes, we assume that the relay node knows the residual energy in CH_i, E_{CH_i}, as well as the power consumption of CH_i with direct or indirect transmission to the BS, denoted by $P_{CH_i,on}$ and $P_{CH_i,off}$ respectively. Our problem is then to determine the amount of time the relay node should serve CH_i, denoted by t_{CH_i}, to achieve maximum network lifetime, i.e., the time until the first CH dies. Table I summarizes the notations used throughout the paper.

TABLE I
NOTATIONS USED THROUGHOUT THIS PAPER

Notation	Description	Value
N_s	Number of sensors in the network	N.A.
N_c	Number of clusters in the network	10
i	CH index	{1,2,. . .,10}
j	Index of iteration	N.A.
E_{CH_i}	residual energy of CH_i	(0,0.5J)
E_s	Energy stored in battery for each sensor	0.5J
$P_{CH_i,off}$	Energy consumption rate for CH_i when relay node is not working	N.A.
$P_{CH_i,on}$	Energy consumption rate for CH_i when relay node is working	N.A.
ΔE	Overhead energy consumption for relay node to select CH	N.A.
$L_{CH_i}^{direct}$	lifetime for CH_i without relay node	N.A.
L	Network lifetime	N.A.
$L_{CH_i}^{relay}$	lifetime for CH_i if it always transmits through the relay node	N.A.
$t_{CH_i}(j)$	time relay node serves CH_i in iteration j	N.A.
t_{CH_i}	total time relay node serves CH_i	N.A.
$t(j)$	time relay node serves CHs in iteration j	N.A.
$x(j)$	the improvement of network lifetime in iteration j	N.A.
$P_{RN,c}$	energy consumption rate for relay node	N.A.

B. Distributed Iterative Algorithm for Relay Node Scheduling

Let $L_{CH_i}^{direct}$ ($L_{CH_i}^{relay}$) denote the lifetime of CH_i if it always transmits *directly* (via the relay node) to the BS, i.e.,

$$L_{CH_i}^{direct} = \frac{E_{CH_i}}{P_{CH_i,off}} \tag{1}$$

$$L_{CH_i}^{relay} = \frac{E_{CH_i}}{P_{CH_i,on}} \tag{2}$$

If $L_{CH_i}^{direct}$ is sorted in increasing order, i.e., $L_{CH_1}^{direct} \leq L_{CH_2}^{direct} \leq L_{CH_3}^{direct} ... \leq L_{CH_{N_c}}^{direct}$, then the network lifetime $L = L_{CH_1}^{direct}$. We propose a relay node scheduling algorithm that iteratively increments the lifetime of $\{CH_1, \cdots, CH_{j-1}\}$ to match the lifetime of CH_j so that network lifetime can be maximized. Let $x(j) = L_{CH_{j+1}}^{direct}$-$L_{CH_j}^{direct}$, as illustrated in Figure 2. Let $t_{CH_i}(j)$ denote the duration that relay node serves CH_i, and $t(j) = \sum_{i=1}^{j} t_{CH_i}(j)$ denote the total time the relay node is serving CHs, in iteration j. We also define α_{CH_i} as follows:

$$\alpha_{CH_i} = \frac{P_{CH_i,off} - P_{CH_i,on}}{P_{CH_i,off}} \tag{3}$$

Since the relay node has initial energy E_s, it can operate for maximum duration of $\frac{E_s}{P_{RN,c}}$, where $P_{RN,c}$ is the rate of energy consumption when it is active.

- **Iteration=1**

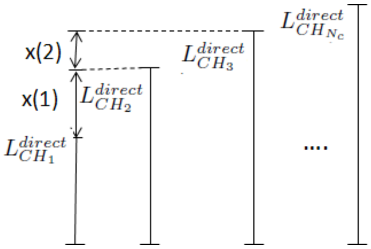

Fig. 2. Abstract model for lifetime expression

We have the following theorem:

Theorem 1. *If* $\frac{E_s}{P_{RN,c}} * \alpha_{CH_1} \geq (L^{direct}_{CH_2} - L^{direct}_{CH_1})$ *and* $L^{relay}_{CH_1} > L^{direct}_{CH_2}$*, then the relay node needs to serve* CH_1 *in iteration 1 for a duration* $t_{CH_1}(1)$ *so that its lifetime is* $L^{direct}_{CH_2}$*, where* $\frac{x(1)}{t_{CH_1}(1)} = \alpha_{CH_1}$

Proof: First, we have the following equation arrays:

$$\begin{cases} E_{CH_1} = L^{direct}_{CH_1} P_{CH_1,off} \\ E_{CH_1} = P_{CH_1,on} t_{CH_1}(1) + \\ (L^{direct}_{CH_1} + x(1) - t_{CH_1}(1)) P_{CH_1,off} \end{cases} \tag{4}$$

According to (4), we have:

$$\frac{x(1)}{t_{CH_1}(1)} = \frac{P_{CH_1,off} - P_{CH_1,on}}{P_{CH_1,off}} \tag{5}$$

Therefore, Theorem 1 is proved. ∎

Following this, the stored energy in the relay node is decremented by $P_{RN,c} * \frac{L^{direct}_{CH_2} - L^{direct}_{CH_1}}{\alpha_{CH_1}}$.

- **Iteration=2**

  The bottleneck nodes are now CH_1 and CH_2, and their lifetime should next be improved (through relay node scheduling) until their lifetime is $L^{direct}_{CH_3}$. We have the following theorem:

  Theorem 2. *If* $\frac{E_s}{P_{RN,c}} * \alpha \geq (L^{direct}_{CH_3} - L^{direct}_{CH_2})$ *where* $\alpha = \frac{1}{\frac{1}{\alpha_{CH_1}} + \frac{1}{\alpha_{CH_2}}}$ *and* $L^{relay}_{CH_i} > L^{direct}_{CH_3} \forall i = (1,2)$*, then the relay node needs to serve* CH_1 *and* CH_2 *in iteration 2 for duration* $t_{CH_1}(2)$ *and* $t_{CH_2}(2)$ *respectively so that their lifetimes are* $L^{direct}_{CH_3}$*, where* $\frac{x(2)}{t(2)} = \frac{1}{\frac{1}{\alpha_{CH_1}} + \frac{1}{\alpha_{CH_2}}}$.

  Proof:

  For CH_1, we have:

$$\begin{cases} E_{CH_1} = P_{CH_1,on} t_{CH_1}(1) + \\ (L^{direct}_{CH_2} - t_{CH_1}(1)) P_{CH_1,off} \\ t_{CH_1}(1) = \frac{L^{direct}_{CH_2} - L^{direct}_{CH_1}}{\alpha_{CH_1}} \\ E_{CH_1} = (t_{CH_1}(1) + t_{CH_1}(2)) P_{CH_1,on} + \\ (L^{direct}_{CH_2} + x(2) - t_{CH_1}(1) - t_{CH_1}(2)) P_{CH_1} \end{cases} \tag{6}$$

  After proper transformation of (5), we have

$$\frac{x(2)}{t_{CH_1}(2)} = \frac{P_{CH_1,off} - P_{CH_1,on}}{P_{CH_1,off}} = \alpha_{CH_1} \tag{7}$$

  Therefore, $\frac{x(2)}{t_{CH_1}(2)} = \alpha_{CH_1}$.

  For CH_2, we have the following equation arrays:

$$\begin{cases} E_{CH_2} = L^{direct}_{CH_2} P_{CH_2} \\ E_{CH_2} = P_{CH_2,on} t_{CH_2}(2) + \\ (L^{direct}_{CH_2} + x(2) - t_{CH_2}(2)) P_{CH_2,off} \end{cases} \tag{8}$$

  After transformation of (8), we have the following (9).

$$\frac{x(2)}{t_{CH_2}(2)} = \frac{P_{CH_2,off} - P_{CH_2,on}}{P_{CH_2,off}} = \alpha_{CH_2} \tag{9}$$

  Hence, $\frac{x(2)}{t_{CH_i}(2)} = \alpha_{CH_i}$ for $i = 1, 2$. Next, using (7) and (9), we derive the relationship between $t(2)$ and $x(2)$ as follows:

$$t(2) = t_{CH_1}(2) + t_{CH_2}(2) = \frac{x(2)}{\alpha_{CH_1}} + \frac{x(2)}{\alpha_{CH_2}} \tag{10}$$

  $\Rightarrow$

$$\frac{x(2)}{t(2)} = \frac{1}{\frac{1}{\alpha_{CH_1}} + \frac{1}{\alpha_{CH_2}}} \tag{11}$$

  ∎

  Following this, the stored energy in the relay node is decremented by $P_{RN,c} * \frac{L^{direct}_{CH_3} - L^{direct}_{CH_2}}{\alpha}$.

- **Iteration=**j

  At iteration j, the relay node will serve CH_i, $1 \leq i \leq j$, until they have the same lifetime as CH_{j+1}. We have the following theorem:

  Theorem 3. *If* $\frac{E_s}{P_{RN,c}} * \alpha \geq (L^{direct}_{CH_{j+1}} - L^{direct}_{CH_j})$ *where* $\alpha = \frac{1}{\sum_{i=1}^{j} \frac{1}{\alpha_{CH_i}}}$ *and* $L^{relay}_{CH_i} > L^{direct}_{CH_{j+1}} \forall i = (1, 2, ..., j)$*, then the relay node needs to serve* $\{CH_1, \cdots, CH_j\}$ *in iteration* j *for duration* $\{t_{CH_1}(j), \cdots, t_{CH_j}(j)\}$ *respectively so that their lifetimes are* $L^{direct}_{CH_{j+1}}$*, where* $\frac{x(j)}{t(j)} = \frac{1}{\sum_{i=1}^{j} \frac{1}{\alpha_{CH_i}}}$

  Proof: For CH_i, i=1,2,$\cdots$,j, we have the following equations:

$$\begin{cases} E_{CH_i} = \sum_{k=1}^{j-1} t_{CH_i}(k) P_{CH_i,on} + \\ (L^{direct}_{CH_j} - \sum_{k=1}^{j-1} t_{CH_i}(k)) P_{CH_i,off} \\ E_{CH_i} = \sum_{k=1}^{j} t_{CH_i}(k) P_{CH_i,on} + \\ (L^{direct}_{CH_j} + x(j) - \sum_{k=1}^{j} t_{CH_i}(k)) P_{CH_i,off} \end{cases} \tag{12}$$

  From (12), we have the following equations:

$$\frac{x(j)}{t_{CH_i}(j)} = \alpha_{CH_1} \forall i = (1, 2, ..., j) \tag{13}$$

  The total time that the relay node needs to serve them is $t(j)$, which is shown below:

$$t(j) = \sum_{i=1}^{j} t_{CH_i}(j) = \sum_{i=1}^{j} \frac{x(j)}{\alpha_{CH_i}} \Rightarrow \frac{x(j)}{t(j)} = \frac{1}{\sum_{i=1}^{j} \frac{1}{\alpha_{CH_i}}} \tag{14}$$

  ∎

In summary, our proposed relay node scheduling algorithm is shown in Algorithm 1. Note that if t_{CH_i}, the total time the

Algorithm 1 Algorithm for relay node to re-select CH

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- Initialization
    Relay node collects $E_{CH_i}$, $P_{CH_i,off}$, $P_{CH_i,on}$ from $CH_i$ and $P_{RN,c}$. Relay node sorts $L_{CH_i}^{direct}$ in an increasing order according to (1) such that $L_{CH_1}^{direct} \leq L_{CH_2}^{direct} ... \leq L_{CH_{N_c}}^{direct}$. It calculates $\alpha_{CH_i}$ and $L_{CH_i}^{relay}$ for $CH_i$ according to (3) and (2). Set $j = 1$.
- Step 1
    If $L_{CH_i}^{relay} > L_{CH_{j+1}}^{direct}$ for $1 \leq i \leq j$, goto Step 2, else goto step 4.
- Step 2
    Let $\alpha = \frac{1}{\sum_{i=1}^{j} \frac{1}{\alpha_{CH_i}}}$. If $(L_{CH_{j+1}}^{direct} - L_{CH_j}^{direct}) > \frac{E_s}{P_{RN,c}} * \alpha$
    Then go to step 4; else, goto Step 3.
- Step 3
    Record $t_{CH_i}(j) = \frac{L_{CH_{j+1}}^{direct} - L_{CH_j}^{direct}}{\alpha_{CH_i}}$. Update $E_s = E_s - P_{RN,c} * \frac{L_{CH_{j+1}}^{direct} - L_{CH_j}^{direct}}{\alpha}$. Set $j = j + 1$. Return to Step 1.
- Step 4
    The network lifetime is thus $L = L_{CH_j}^{direct} + \frac{E_s}{P_{RN,c}} * \alpha$. Also, $t_{CH_i} = \frac{L - L_{CH_i}^{direct}}{\alpha_{CH_i}}$.
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relay node is scheduled to serve CH_i, is greater than the time slot duration, T, then it will serve CH_i for several rounds N until $N * T \leq t_{CH_1}$ and $(N + 1) * T > t_{CH_1}$; CH_i will transmit directly to the BS in subsequent rounds.

The algorithm is found to converge as it will terminate once $L < L_{CH_{j+1}}^{direct}$.

IV. SIMULATION RESULTS

We validate our results through simulations for clustered WSN with 10 clusters, each composing 20-30 sensor nodes. In each round, each node needs to transmit a 2000-bit packet at a rate of 250 kbps. We set the slot duration to be T=0.016s, E_s = 0.5J, and assume the Friss free space propagation model. We benchmark our proposed relay scheduling algorithm with (i) a periodic algorithm and (ii) direct CH-BS transmission. In the periodic algorithm, the relay node exchange information with the CH nodes in the beginning of each round, and serves the CH with the lowest lifetime in that round.

We consider two square regions of network deployment, where the coordinates of the vertices are as follows: Area (I) (100, 100), (100, 200), (200, 100) and (200, 200); Area (II) (100, -50), (100, 50), (200, -50), (200, 50). The relay node is deployed at six different positions as follows: Case (I) (50,50); Case (II) (60,60); Case (III) (70,70); Case (IV) (50,0); Case (V) (60,0); Case (VI) (70,0);

We plot the time until each CH runs out of energy for each algorithm for {Case (I), Area (I)} and {Case (II), Area (I)} in Figure 3a and 3b respectively. As expected, direct transmission to the BS results in the worst network lifetime (10 rounds). The periodic approach increases the lifetime of CH_1 to CH_3, resulting in a network lifetime of 20 rounds. While our proposed approach is more complex than the periodic approach, it has lower overhead as it does not require message exchange in every round, resulting in a significant gain in network lifetime. The network lifetime is higher in Case II as the relay node was deployed closer to the WSN, resulting in lower power consumption by the CHs.

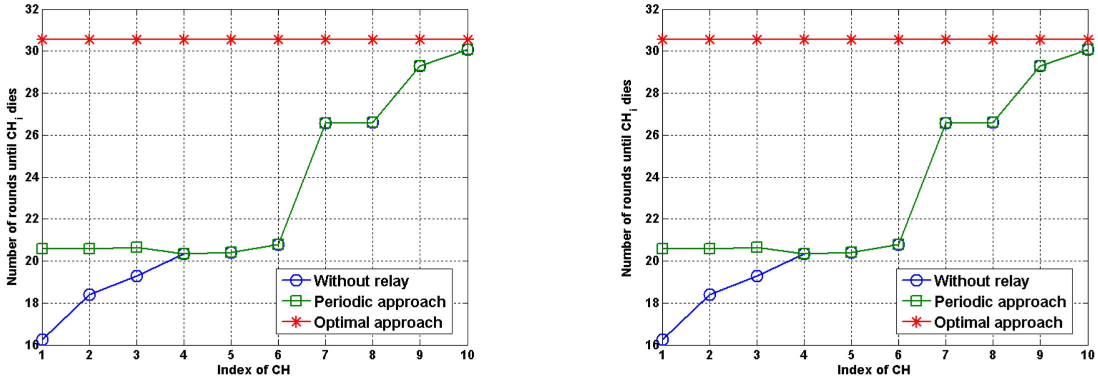
Next, we compare the network lifetime (i.e., time till the first CH node dies) obtained with each algorithm for all six cases in Figure 4a. While our proposed approach achieves the highest network lifetime in all cases, the periodic approach yields better performance than direct CH-BS transmission except for {Case (V), Area (II)} and {Case (VI), Area (II)}. This is because the energy savings by transmitting via the relay node is smaller than the cost of energy overhead for relay node reselection in each round. Amongst the various scenarios, our approach achieves the best performance for {Case (II), Area (I)} and {Case (VI), Area (II)}. This can be explained as follows: In Case (II), the relay node can serve all CHs for a longer time (163.38 rounds) than in Case (III) (121.38 rounds) since the relay node is closer to the BS in Case (II) than in Case (III) which leads to a smaller energy consumption. For Case (I), CH_1 is farther from the relay node than in Case (II), which results in a shorter lifetime (27 rounds compared to 30.56 rounds in Case (II)).

Lastly, we plot the number of rounds the relay node serves each CH with our proposed approach and the periodic approach for {Case (II), Area (I)} in Figure 4b. We find that the relay node serves all CHs under our approach while it only serves the first two CHs under the periodic approach. The total relay node working time for CH_1 is improved by 15 rounds for our approach compared with periodic approach. This can be explained as follows: for the periodic approach, 0.015 J energy is spent on re-selection of CHs, which reduces the number of rounds it serves CH_1 by 15 compared with the optimal approach.

V. CONCLUSION AND FUTURE WORK

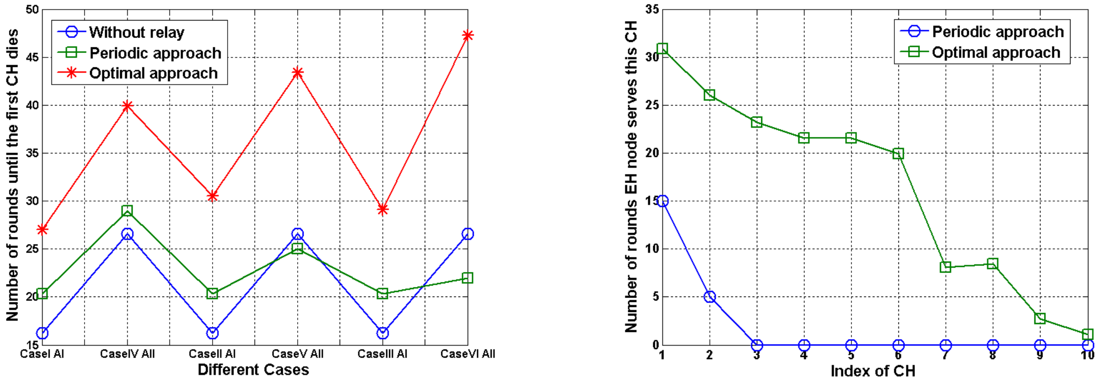
In this paper, we consider a clustered wireless sensor network that transmits sensed data, either directly, or via a relay node, to a base station. Given that cluster heads are selected, clusters are formed and the relay node is placed, we proposed an optimal distributed algorithm for scheduling the relay node to serve the cluster heads to maximize network lifetime. Through extensive simulations, we verified the improvement in network lifetime by transmitting via the relay node, and that our proposed algorithm achieves better network lifetime compared to a greedy approach that periodically re-selects the cluster head with the shortest lifetime to serve. While our proposed algorithm is more complex, it incurs much lower overhead compared to the periodic approach, which requires periodic exchange of messages between the cluster heads and the relay node.

The current network model may be limited by the finite lifetime of the relay node. To this end, we plan to extend our work to the case where the relay node is replaced by an energy harvesting node, whose energy can be replenished. In addition, we plan to incorporate realistic energy models



(a) (b)

Fig. 3. Number of survival rounds of each CH for (a) Case I and Area I (b) Case II and Area I



(a) (b)

Fig. 4. (a) Comparison of network lifetime for six different cases (b) Number of rounds relay node serves for each CH

through extensive measurements on solar cells into our future study. In the long term, we hope to implement and evaluate our proposed clustering algorithms in an actual environment.

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