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Near-Minimum-Energy Routing in Heterogeneous Wireless Sensor Networks

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***Abstract*—Routing is an essential operation in wireless sensor networks. Most existing routing protocols are designed for homogeneous sensor networks. Recent studies [5],[11] show that a homogeneous sensor network has a poor fundamental performance limit. To achieve better performance, we adopt a Heterogeneous Sensor Network (HSN) model. In this paper, we present an efficient *NEar-optiMal rOuting* (NEMO) protocol for HSNs. We evaluate the performance of NEMO through extensive simulation experiments. Our results show that NEMO can find near-optimal routes in an HSN and has very small overhead.**

***Keywords*: Heterogeneous sensor networks; energy efficiency; routing protocols; embedded systems.**

I. Introduction

The primary functionality of wireless sensor networks is to sense the environment and transmit the acquired information to a base station (BS) for further processing. Thus, routing is a fundamental and very important operation in sensor networks. Routing in homogeneous sensor networks has been well studied, and a number of routing protocols [6],[8],[13],[14] have been proposed. To achieve better performance, we adopt a realistic Heterogeneous Sensor Network (HSN) model [4], which includes different physical types of sensor nodes, and some nodes are more powerful than other nodes. In [12], Yarvis *et al.* studied some design issues in a special type of HSN, where some sensor nodes are line powered and have unlimited energy supply, and all other nodes are just onehop away from the line powered nodes. In [10], Mhatre *et al.* studied minimum node densities and energies in HSNs to guarantee a network lifetime. In [2], Du *et al.* designed an efficient routing protocol, Heterogeneous Sensor Relay (HSR), for HSNs. To the best of our knowledge, it is one of the most effective routing schemes designed for HSNs. However, most previous approaches are not distributed and could cause a large time and message complexity.

In this paper, we present an efficient *distributed* routing protocol- NEar-optiMal rOuting (NEMO)-for HSNs. The (near) optimal routing in this paper refers to (near) minimum-energy-consumption routing. The NEMO protocol achieves impressive performance by utilizing more powerful H-sensors in an HSN. Simulation results show that NEMO achieves near-minimum energy consumption and has much less time and message complexity than the centralized optimal solution.

Our contributions in this work are four-fold: First, the proposed NEMO protocol can find near-optimal routes in terms of energy consumption. Second, compared with the traditional shortest path algorithm, the NEMO protocol can significantly reduce the communication overhead. Third, we propose a novel and effective distributed shortest path algorithm for resource-limited sensor networks. Fourth, we study a new problem, Weighted Energy-Aware Routing (WEAR), in HSNs, which considers the fact that *an H-sensor has much more energy supply than an L-sensor*.

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The rest of the paper is organized as follows: in Section II, we present the problem statement. The technical details of the NEMO protocol are presented in Section III, which is followed by the simulation experiments and results in Section IV. We conclude the paper in Section V.

II. Problem Statement

One fundamental research issue in sensor networks is energy efficient routing, which is due to the limited energy of sensor nodes. Our current HSN model consists of a small number of powerful H-sensors and a large number of L-sensors. All H-sensors form a backbone in an HSN. After a cluster formation, an HSN is divided into multiple clusters, and H-sensors serve as cluster heads.

We adopt the first order radio model presented in [6]. A sensor consumes ϵ_{elec}=50 *nJ/bit* to run the transmitter or receiver circuitry and ϵ_{amp}=100 *pJ/bit/m*^{2} for the transmitter amplifier. Thus, the energy consumed by a sensor then receiving a 1-bit data packet is given by $R_x = \epsilon_{elec}$, while the energy consumed by sensor *i* in transmitting a data packet to sensor *j* is given by $T_x = (\epsilon_{elec} + \epsilon_{amp} \cdot d_{i,j}^2)$, where $d_{i,j}$ is the distance between nodes *i* and *j*.

Definition 1 (Minimum Energy Routing): Denote the energy consumption of relaying a packet by an L-sensor and an H-sensor as e_l and e_h, respectively. The path energy consumption of P_l, a path from an L-sensor l to the BS, is $EC(P_l) = \sum_{l_i \in P_l} e_{l_i} + \sum_{h_i \in P_l} e_{h_i}$. Let Π represent the set of all possible paths, L be the set of all L-sensors, l be an L-sensor, and P_l be a path from l to the BS. Minimum energy routing in HSNs seeks paths for all L-sensors with the objective $\min_{P_l \in \Pi} \sum_{l \in L} EC(P_l)$. In other words, the total energy consumption from all L-sensors to the BS should be minimized. □

III. Near-Minimum-Energy Routing

To minimize the *total* routing energy, we aim to find the minimum energy path *from each L-sensor to the BS*. However, in large wireless sensor networks, finding shortest paths for a large number of L-sensors in a distributed manner could cause substantial communication (message) overhead, and hence, cause significant energy consumption of sensor nodes. In this paper, we present the NEMO protocol, which is listed in Algorithm 1. Adopting the two-tiered architecture in [2],

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NEMO finds a near-minimum-total-energy route for an L-sensor to the BS in the network and incurs small overhead. We first introduce a concept which helps NEMO to reduce the time and message complexity.

Definition 2 (Eligible H-sensor): Given an energy consumption threshold τ, an eligible H-sensor for an L-sensor l is an H-sensor h such that there exists a path $l \rightarrow h \rightarrow BS$, whose energy consumption is no more than τ. □

Algorithm 1 NEMO(G)

1: **for** each H-sensor *h* in *G* **do**
2: Find a shortest path from *h* to *BS*;
3: **end for**
4: **for** each L-sensor *l* in *G* **do**
5: Find *eligible* H-sensors for *l*;
6: Calculate a shortest path from *l* to each *eligible* H-sensor;
7: **end for**
8: Find the route from each L-sensor *l* to BS with the minimum total energy consumption.

The purpose of using *eligible* H-sensors is to reduce the overhead of route discovery. First, each H-sensor computes a path to the BS with minimum energy consumption (denoted as E_1). Next, each L-sensor *l* computes a path to every eligible H-sensor and the corresponding energy consumption (denoted as E_2). Then, an L-sensor *l* finds the path that has the minimal E_1+E_2 as the path from *l* to the BS. In the next Section, we discuss the details of our novel distributed shortest path algorithm for the NEMO protocol.

A. Determining Eligible H-sensors

One major contribution in this work is that we propose a theoretical analysis of choosing eligible H-sensors. By only using the Euclidian distance between an L-sensor and an H-sensor, we have the following lower bound of energy consumption.

Lemma 1: Given an L-sensor l and an H-sensor h, and the Euclidian distance d between them, the energy for transmissions from l to h is no less than $2d\sqrt{\epsilon_{elec}\epsilon_{amp}}$. □

Proof: Theoretically, the shortest (minimum energy) path should be on the straight line connecting *l* and *h*, as we show in Fig. 1(a). For simplicity, we use k_1 and k_2 to represent ϵ_{elec} and ϵ_{amp}, respectively.

Denote p_1 as the best path along the straight line between *l* and *h*, and p_2 as another path from *l* to *h*. First, we aim to calculate the theoretical optimum energy consumption on p_1, which depends on the number of intermediate nodes and the placement of these nodes. Let *x* and $EC(x)$ denote the number of edges on p_1 and the energy consumption of the path using *x* edges, respectively. There are two cases to consider:

Case 1: Nodes are distributed evenly

We can obtain the expression of $EC(x)$ as follows:

$$y_1 \equiv EC(x) = 2k_1x + k_2\frac{d}{x}^2 \quad (1)$$

It is easy to see that $y_1 \geq \sqrt{4 \cdot k_1 \cdot x \cdot k_2 \cdot \frac{d^2}{x}} = 2d\sqrt{k_1 \cdot k_2}$. Therefore, the theoretical minimum for $EC(x)$ is $2d\sqrt{k_1k_2}$, when the number of edges $x = d\sqrt{\frac{k_2}{2k_1}}$. Note that the actual minimum $EC(x)$ may be larger than $2d\sqrt{k_1 \cdot k_2}$, since $d\sqrt{\frac{k_2}{2k_1}}$ may not be an integer.

Case 2: Nodes are not distributed evenly

As shown in Fig. 1(b), we have:

$$y_2 \equiv 2 \cdot x \cdot k_1 + k_2\left(d_1^2 + d_2^2 + \ldots + d_x^2\right) \quad (2)$$

Comparing (1) and (2), we have observed that:

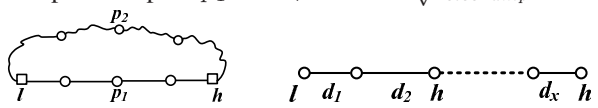
$$y_1 = 2k_1x + k_2\frac{(d_1+d_2+\ldots+d_x)^2}{x}$$

$$y_2 = 2k_1x + k_2(d_1^2 + d_2^2 + \ldots + d_x^2)$$

It is well-known that the *quadratic Mean* of d_i $(1 \leq i \leq x)$ is no less than the *Arithmetic Mean* of them. We have:

$$\frac{d_1+d_2+\ldots+d_x}{x} \leq \sqrt{\frac{d_1^2+d_2^2+\ldots+d_x^2}{x}}$$

Therefore, $y_1 \leq y_2$. With the same number of intermediate nodes, *energy consumption is always smaller when nodes that are distributed evenly*. Hence, the theoretical minimum energy consumption of path p_1 is $2d\sqrt{k_1k_2} = 2d\sqrt{\epsilon_{elec}\epsilon_{amp}}$.



(a) Illustration of the optimal estimate (b) Illustration of uneven distribution case

Fig. 1. Illustration of lemma 1

Next, we need to compare the energy consumption between p_1 and p_2. For any instance of p_2 with *x* edges, it is easy to construct a corresponding case of p_1 that also has *x* edges. Because the length of p_1 is less than that of p_2, we can divide p_1 into *x* segments, and the length of each segment (edge) is no more than the corresponding edge on p_2. Based on the formula of energy consumption, it is straightforward to see that p_1 must have less energy consumption than p_2. Meanwhile, as proved above, an instance of p_1 with evenly distributed edges has less energy consumption than an instance of p_1 with unevenly distributed edges. Therefore, the minimum energy consumption path is on p_1, with even distributed edges, which is no less than $2d\sqrt{\epsilon_{elec}\epsilon_{amp}}$. ■

Based on Lemma 1, we present the following scheme for selecting eligible H-sensors:

Scheme 1 (Selecting Eligible H-Sensor): Given a threshold τ, and an H-sensor h, denote EC_h as the minimum energy consumption from h to the BS, which is calculated in Algorithm 1. If $(EC_h + 2d\sqrt{\epsilon_{elec}\epsilon_{amp}}) \leq \tau$, then h is considered as an eligible H-sensor. □

Theorem 1: All the eligible H-sensors can be found by Scheme 1. In other words, any H-sensor that is excluded by Scheme 1 is not an eligible H-sensor. □

Proof: For an H-sensor *h*, assume that the estimated path energy consumption is higher than the threshold:

$$(EC_h + 2d\sqrt{\epsilon_{elec}\epsilon_{amp}}) > \tau$$

Denote EC_l as the actual minimum energy consumption from an L-sensor *l* to the H-sensor *h*. Based on Lemma 1, we have:

$$EC_l \geq 2d\sqrt{\epsilon_{elec}\epsilon_{amp}}$$

Consequently, we know $(EC_h + EC_l) > \tau$. Thus, the actual path ($l \rightarrow h \rightarrow BS$) consumes more energy than τ. And it is guaranteed that *h* is not an eligible H-sensor and should be excluded. Therefore, all the H-sensors excluded by Scheme 1 are ineligible H-sensors. ■

B. Distributed Shortest Path Algorithms

In this section, we propose a distributed algorithm, based on the work in [1],[3], to find shortest paths from a source

node to all other nodes in the network with *arbitrary integer edge costs*. On one hand, our algorithm is simple and does not require strong storage and computational capability. Thus, it is easy to be implemented in sensor networks. On the other hand, the algorithm has time and message complexity guarantees, while the Ford-Bellman method does not [7].

In Algorithm 2, G is the network, and r represents the root node. Each node has two statuses: *black* or *white*. Initially, every node, except the root node, is *white*, which means that it does not have a shortest path to the root node, yet. The root node is initialized as black. When a node finds its shortest path to the root node, it will be marked as black. There are four types of messages; *hello, MARK*, *NOTYET*, and *NAK*, which will be used on the edges of the network. Our algorithm works in successive iterations. Each *black* node will generate (as the root node) or forward (as a non-root node) a *hello* message in each iteration, with the beginning of each iteration synchronized by the root node r. In Algorithm 2, $c(e)$ and *hello_num*(*e*) indicate the cost of edge e and the number of the *hello* messages received through e, respectively.

Algorithm 2 DisSPT(*G, r*)

```
1: for each node v in G do
2:    if (v == r) then
3:       mark v as black;
4:    else
5:       mark v as white;
6:    end if
7: end for
8: for each edge e in G do
9:    hello_num(e) = 0;
10: end for
11: repeat
12:    u = r; done = 1; Broadcast(u); // Algorithm 3
13:    Wait until receiving responses from all neighbor nodes of u;
14: until (done)
```

It is worth noting that Algorithm 2 is simple and has a performance guarantee. The difference between Algorithm 2 and the DFS algorithm in [1] is when each *white* node receives a *hello* message from an edge, it will compare the number of *hello* messages received from the edge with this edge's cost before response. If the number of the received messages is equal to the edge cost, this node, which is still *white*, will mark itself *black*, send a *MARKED* message back to the sender along the edge, and set the sending node as its parent. Otherwise, it will send a *NOTYET* message to the sender, which indicates that the node is not sure, at this point, if the incoming edge is on the shortest path. We prove the performance of Algorithm 2 in Theorem 2 by using a novel graph transformation scheme to show the relation between work in [1] and Algorithm 2.

Theorem 2: Algorithm 2 finds shortest paths from the root node to all other nodes, correctly. The communication complexity and the time complexity are $O(C^2+(m-n)^2)$, where C is the summation of all edge costs and n and m are the number of the node and edges in the network, respectively. □

Proof: Let us construct a graph transformation to demonstrate our idea behind Algorithm 2 and the proof. First, we transfer an original network *G* in Fig. 2(a) to the network *G'* in Fig. 2(d). For each link *e* with edge cost $c(e)$ in *G*, it is split into $c(e)$ edges in *G'*. For example, link (*A,B*) in *G*, with edge cost 3, is split into 3 edges (*A*,b^1), (b^1, b^2), and (b^2, B) in *G'*, which is a network with same edge cost, which is studied in [1]. In Fig. 2(b), when white node *B* receives a *hello* message from root *A*, it compares the number of the messages received from this edge, which is 1, with the edge cost 3. Since the number of *hello* messages is less than the edge cost, a *NOTYET* message is sent back to node *A* (Lines 10-14 in Algorithm 3).

Algorithm 3 Broadcast(u)

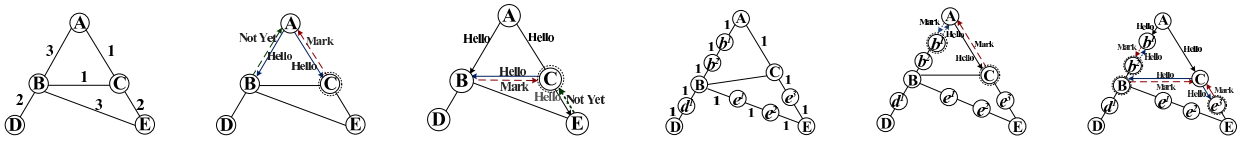
```
1: Node u sends out hello message to each neighbor v;
2: for each neighbor node v do
3:    if (v is black) and (u is v's parent) then
4:       Broadcast(v);
5:       Wait until received responses from all neighbor nodes;
6:       Send information back to u;
7:    else
8:       if (v is white) then
9:          e = (u, v);
10:         if (hello_num(e) < c(e) - 1) then
11:            Send message NOTYET to the sending node u;
12:            hello_num(e)++; done = 0;
13:         else
14:            Mark node v as black;
15:            Send message MARKED to the sending node u;
16:            Make node u as node v's parent; done = 0;
17:         end if
18:      end if
19:   end if
20:   send message NAK to node u;
21: end for
```

The corresponding case, in Fig. 2(e), is that node b^1, *instead of node B*, receives a *hello* message from node *A*. Node b^1 is marked as black, sends a *MARK* message back to *A*, but *B* still does not find the shortest path and *white*. Meanwhile, node *C* is marked as black in both cases because the cost of edge *(A, C)* is 1. In the next iteration in *G*, in Fig. 2(c), a *hello* message reaches node *B* again. Correspondingly, in *G'*, a *hello* message reaches node b^2 (not node B) in Fig. 2(f). Node *B* will send a *NOTYET* message back to *A* again in Algorithm 3. Meanwhile, node *C* reaches node *B* in both cases, thus node *B* is marked as black and sets node *C* as its parent, which implies that *B* found a shortest path to node *A* through edge *(B,C)*. Following the process, we can see that *Algorithm 2, working on network G, equals finding a DFS tree on transformed graph G' with a unified edge cost*, which was studied in [1], and will deliver correct results.

As for the complexity of the algorithm, we can see that the total number of messages on the edges in G equal to the total number of messages on the transformed graph *G'* using schemes in [1]. On the transformed graph *G'*, the number of edges is the summation of all edge costs, $C = \sum_{i=1}^{m} c_i$. The number of newly added nodes is $\sum_{i=1}^{m}(c_i - 1)$, thus the total number of nodes in the transformed networks is (*C*-(*m*-*n*)). Following the work from [1], we can see that the message complexity and the time complexity of Algorithm 2 are both $O(C^2 + (m-n)^2)$. ■

C. Weighted Energy-Aware Routing in HSNs

In the above NEMO routing protocol, the cost of one Joule energy consumption of an H-sensor is considered the same



(a) Network G (b) Iteration 1 on G (c) Iteration 2 on G (d) Network G' (e) Iteration 1 on G' (f) Iteration 2 on G'

Fig. 2. Graph transformation for Algorithm 2

as that of an L-sensor. However, an H-sensor usually has a larger energy supply than an L-sensor has. Thus, the cost of consuming one Joule of energy in an H-sensor should be modeled lower than that in an L-sensor. To consider such a fact in the routing protocol design and optimization, we study the *Weighted Energy-Aware Routing* (WEAR) problem. We consider a modified objective function by applying a discount factor $\alpha(0 < \alpha < 1)$ for energy consumption of H-sensors, i.e., we aim to find a path that minimizes the following objective function:

$$\min_{P\in\Pi}\{\sum_{i\in P} e_{L_i} + \alpha \sum_{j\in P} e_{H_j}\}$$

Correspondingly, there are four types of edges:

1) L-sensor to L-sensor edge:
   $EC = (T_x + R_x) = (2 \cdot \epsilon_{elec} + \epsilon_{amp} \cdot d_{i,j}^2)$
2) L-sensor to H-sensor/BS:
   $EC = T_x + \alpha \cdot R_x = (1 + \alpha) \cdot \epsilon_{elec} + \epsilon_{amp} \cdot d_{i,j}^2$
3) H-sensor/BS to L-sensor:
   $EC = \alpha \cdot T_x + R_x = (1 + \alpha) \cdot \epsilon_{elec} + \alpha \cdot \epsilon_{amp} \cdot d_{i,j}^2$
4) H-sensor/BS to H-sensor/BS:
   $EC = \alpha \cdot (T_x + R_x) = \alpha \cdot (2 \cdot \epsilon_{elec} + \epsilon_{amp} \cdot d_{i,j}^2)$

NEMO can be easily modified for the WEAR problem. The basic idea is that the energy consumption of each edge needs to be updated, corresponding to the above formulas. One critical question is to decide the types of edges on the paths because different types of edges have different energy consumptions. In our solution, we find a sub-path p_l from a source L-sensor l to an H-sensor h, and another sub-path p_h from h to BS. In the following theorem, we prove that the shortest (minimum energy) path p_l has only L-sensors as the intermediate nodes between l and h.

Theorem 3: The minimum energy path from an L-sensor l to an eligible H-sensor h only includes L-sensors. That is, this path does not include any other H-sensors. □

Proof: We use Fig. 3 to illustrate the proof. Assume that the minimum energy path from l to h has not only L-sensors, but also H-sensors as intermediate nodes. Let *h'* be the first intermediate H-sensor on the path (note that from l to *h'* all the intermediate nodes are L-sensors).

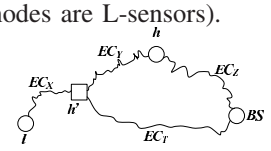


Fig. 3. Illustration for Theorem 3

Denote the energy consumption of sub-path (*l,h'*), (*h',h*), and (*h,BS*) as EC_X, EC_Y, and EC_Z, respectively. Meanwhile, suppose the energy consumption of the shortest path from H-sensor *h'* to the BS is EC_T. Since path (*h', BS*) is the minimum energy path from *h'* to the BS, we have $EC_T \leq EC_Y + EC_Z$. Consequently, $EC_T + EC_X \leq EC_X + EC_Y + EC_Z$, which implies that path *l*→*h'*→*BS* has smaller energy consumption than path *l*→ *h* → *BS*. This implies that we can find another path *l*→*h'*→*BS*, which uses H-sensor *h'* and has less energy consumption. Also, note that this path uses all L-sensors between *l* and *h'*. Following the similar process, we can *always find a path with a smaller energy consumption* and without using any H-sensors between *l* to its eligible H-sensor. Therefore, the shortest path from an L-sensor to its eligible H-sensor only includes L-sensors. ■

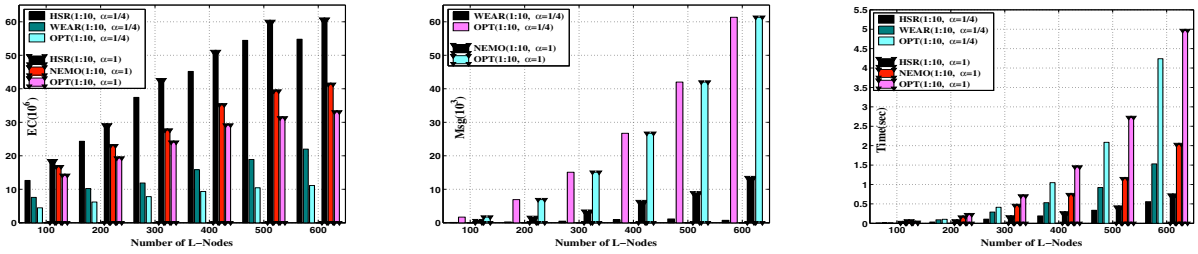
Based on the theorem, for the minimum energy path from an L-sensor *l* to an eligible H-sensor *h*, only the last receiver is an H-sensor. Hence, we need apply the discount factor α to the receiving energy for select eligible H-sensors.

IV. Performance Evaluation

We evaluated the performance of the NEMO protocol extensive simulations. Our simulations were implemented in LEDA [9], a C++ based network simulation tool. All tests were performed on a 1.0GHz Linux PC with 1GB of memory. Both L-sensors and H-sensors were uniformly distributed in a square playing field of 100×100 square units. One base station was randomly deployed in the area. We ran simulations on randomly generated network topologies with different numbers of L-sensors, including 100, 200, 300, 400, 500, and 600. Given the number of L-sensors, we define the *network density* with the ratio between the number of H-sensors and that of L-sensors. In the simulations, 3 different network ratios were studied: $\frac{1}{10}$ (sparse network), $\frac{1}{4}$(medium network), and $\frac{1}{2}$ (dense network). Therefore, a total of 18 different network models have been tested in the evaluation. For each network model, 10 topologies were generated for tests. All figures in this section are the average results of 10 network topologies. The transmission range of an L-sensor is r = 25, and the transmission range of an H-sensor is R = 50. We compared the proposed NEMO protocol with two other routing protocols; the routing protocol in [2] (denoted as HSR), and an optimal solution (denoted as OPT), *which is obtained by using a global shortest path algorithm in the network*.

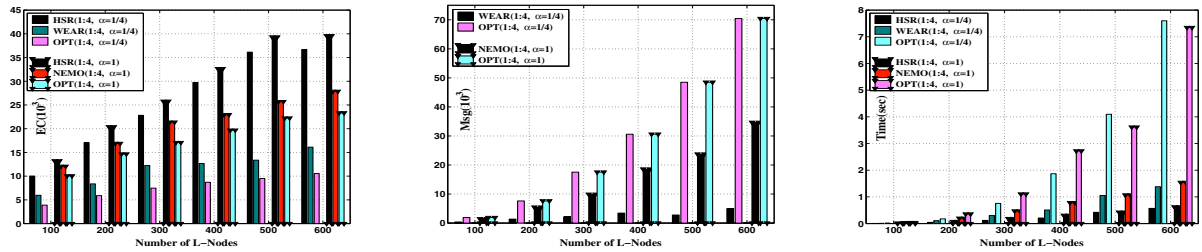
Fig. 4 shows the results for sparse networks. In Fig. 4(a), with both $\alpha = \frac{1}{4}$ and α = 1, we can see that OPT always has the minimum energy consumption. NEMO *has comparable performance with* OPT. Both are obviously better than HSR. Meanwhile, *note that when* $\alpha = \frac{1}{4}$ *(the* WEAR *problem), the energy consumption, as expected, is less than the case with* $\alpha = 1$. This is due to the energy consumption discount, mentioned in Section III-C, on H-sensors. *With the energy consumption close to the optimal solution,* NEMO *has the advantages over* OPT *in both message complexity and time complexity*, as shown in Figs. 4(b) and 4(c). To sum up, NEMO achieves a good balance between small energy consumption and low complexity.

As shown in Figs. 5 and 6, similar results hold for medium and dense networks. *This demonstrates that our* NEMO *routing*



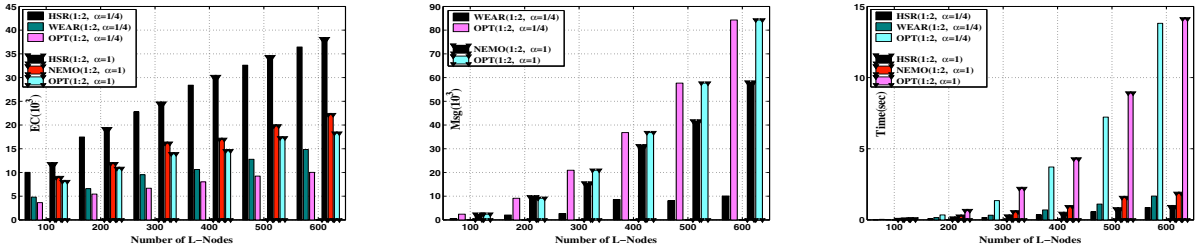
(a) Energy Consumption (b) Message Complexity (c) Running Time

Fig. 4. Results for *sparse* networks (*R=50, r=25*)



(a) Energy Consumption (b) Message Complexity (c) Running Time

Fig. 5. Results for *medium* networks (*R=50, r=25*)



(a) Energy Consumption (b) Message Complexity (c) Running Time

Fig. 6. Results for *dense* networks (*R=50, r=25*)

protocol has very good energy consumption performance, as well as low message and time complexity for all kinds of network topologies. Another observation is that *the denser the network, the less the energy consumption*, as shown in Figs. 4(a), 5(a), and 6(a). The reason is that when the density is higher, there are more H-sensors in the network, which helps to find better paths for L-sensors. It is worth noting that we also evaluated the performances with different transmission ranges (when *R=r*, *R=4r*, etc), which cannot be listed here due to the space limit. For these cases, we observed similar trends, as shown in Figs. 4-6. To sum up, our simulations demonstrated that the NEMO protocol achieves similar energy consumption as the optimal solution, while significantly reducing the message and time complexity. Hence, the NEMO protocol is very suitable for resource-limited sensor networks.

V. Conclusion

In this paper, we presented an efficient Near-Optimal routing (NEMO) protocol for Heterogeneous Sensor Networks. We proposed a new concept - *eligible H-sensor*, and it is used to significantly reduce the routing overhead (including both message and time complexity) of NEMO. Furthermore, we proposed a simple, yet effective distributed shortest path algorithm, and obtained the time and message complexity of the algorithms. Our simulation results show that the NEMO protocol can find near-minimum energy routes and has much smaller routing overhead than the optimal solution.

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