Q-NHEED: A Quad-based Hierarchical Routing Protocol in Wireless Sensor Networks

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Abstract— Hierarchical-based routing protocols play an essential role in both supporting the large scale of networks and decreasing the energy consumption for wireless sensor networks (WSNs). The design of routing protocols must take in account the energy consumption in order to prolong a lifetime of the networks. In this paper, an improved hierarchical routing protocol with multi-hop fashion based on NHEED protocol, named Q-NHEED, is proposed. The aim of the proposed protocol is to extend the network lifetime and provide an efficiency of energy usage by selecting four representative cluster heads for aggregating data and transmitting it to the base station. The simulation results show that the proposed protocol outperforms the traditional HEED and NHEED protocols in points of view a network lifetime and residual energy in each round.

Keywords- hierarchical-based routing protocols, multi-hop routing, wireless sensor networks, HEED, NHEED

I. INTRODUCTION

An increasingly growth of the Internet of Things (IoT) has creating new challenges of basic innovations to form of smart cities [1], [2]. IoT refers to an enormous number of devices that is now connected to the Internet for collecting and sharing information. Wireless Sensor Networks (WSNs) have recently emerged as a significant platform in IoT environments corresponding to the overall networking and IoT connectivity [2], [3]. In recent years, WSNs are widely deployed for several applications in various domains, such as environment monitoring, traffic control and so on [4]. Generally, WSNs are formed of considerable sensor nodes with restricted capacities of processing, communication and battery power. These sensor nodes are autonomously distributed and accommodated to sense, process and convey environment conditions wirelessly, such as temperature, humidity, pressure and so on, to a base station. However, the energy of the sensor nodes is restricted and typically cannot be re-charged during use [4]-[6]. Therefore, the minimization of energy consumption is a critical issue for WSNs in order to provide a prolonged network lifetime [4]-[9]. It is important to choose the suitable and efficient routing protocols with minimizing power consumption in WSNs.

Routing protocols in WSNs are categorized into three groups: flat-based, hierarchical-based, and location-based protocols [1], [10]. Among these, hierarchical-based routing protocols provide an efficient way to prolong the network lifetime of WSNs with clustering method [7], [11]. Data transmission for hierarchical-based routing protocols can be divided into two types: intra-cluster communication and inter-cluster communication. In the intra-cluster communication, the regular sensor nodes collect the data and send them to its cluster head (CH). In the inter-cluster communication, the cluster heads send the collected data to a base station by single-hop or multi-hop routing. With a single-hop routing, the cluster heads directly send the collected data to the base station. This scenario makes the cluster heads which are far away from the base station consume a massive energy and die quickly. In contrast, with a multi-hop routing, the cluster heads which are far away from the base station send the data to a next-hop cluster head which is near to the base station. This approach reduces the energy consumption used by data transmission between the cluster heads.

There are main hierarchical-based routing protocols in past few years, such as LEACH [5], the extensions of LEACH [12]-[19], HEED [8], [14] and NHEED [9]. In LEACH-based protocols, the cluster heads is randomly elected. The low-energy sensor nodes and high-energy sensor nodes has the same probability to be elected as a cluster head. On the other hand, HEED and NHEED proposed an improved method for cluster head selection by considering two parameters: residual energy and intra-cluster communication cost (i.e., node degree) with multi-hop fashion. The difference between HEED and NHEED is the method for the next-hop cluster head selection for multi-hop routing. In HEED, the next-hop cluster head is selected by the nearest neighbor cluster heads. In contrast, both residual energy and distance of neighbor cluster heads are used for selecting the next-hop cluster head in NHEED. In particular in NHEED, some cluster heads will directly transmit the data to the base station if the base station is in their arbitrary communication range. Otherwise, the next-hop cluster head with the minimum cost among the neighbor cluster heads is identified. It is difficult to determine the optimal communication range of cluster heads when size of network area is varied.

In this paper, an improved multi-hop protocol for wireless sensor networks based on NHEED (named Q-NHEED) is proposed. The proposed protocol includes three phases: Clustering, Routing Determination, and Data Transmission. Clustering method is the same as NHEED by accounting the sensor nodes with higher residual energy and dealing with isolated nodes. In the routing determination, four cluster heads, which are near the base station than others, are chosen and responsible for transmitting the data to base station. Both residual energy and distance between cluster heads are accounted for selecting a next-hop cluster head. Finally, the data transmission is started after an optimal route is determined.

The remainder of this paper is organized as follows. Section 2 describes the HEED and NHEED routing protocols and states the problem that we address in this work. Section 3 presents the proposed routing protocol (Q-NHEED) with multi-hop communication based on NHEED. Section 4 shows the simulation results and analysis of Q-NHEED comparing with HEED and NHEED routing protocols. Finally, we concluded the major finding in Section 5.

II. RELATED WORK

A. HEED [8]

HEED (Hybrid Energy Efficient Distributed) is a distributed and hierarchical routing protocol by dealing with few disadvantages of LEACH-based routing protocols. The cluster heads are not randomly selected but they are elected by two parameters: residual energy and intra-cluster communication cost. Furthermore, HEED protocol uses a single-hop model for intra-cluster communication and a multi-hop model for inter-cluster communication. The primary parameter is used to select an initial set of cluster heads according to its residual energy, and another parameter is used to solve the conflict when a regular sensor node is in many cluster heads at the same time. The clustering process of HEED routing protocol can be divided into 3 phases: Initialization phase, Repetition phase, and Finalization phase.

In the initialization phase, all sensor nodes are defined the probability of becoming a cluster head, CH_{prob}, as follows.

$$CH_{prob} = \max\left(C_{prob} \times \frac{E_{re}}{E_{max}}, p_{min}\right) \qquad (1)$$

where C_{prob} is an initial fraction of cluster heads among all sensors, E_{re} is the current residual energy in the sensor node and E_{max} is a maximum energy (corresponding to a fully charged battery). The CH_{prob} value of the node is not allowed to fall below a certain threshold p_{min} (e.g., 10^{-4}).

In repetition phase, each node doubles its CH_{prob} and goes to next iteration of this phase. When its CH_{prob} reaches 1, it stops executing this phase and elect itself to be a cluster head and broadcast a message to its neighbor nodes. Other sensor nodes go through several iterations until find a cluster head with the least communication cost. In finalization phase, each node makes a final decision to either join the cluster head with the least communication cost or elect itself as a cluster head. For data transmission, the regular sensor node transmits the collected data to its cluster head in a single hop and then the cluster head sends the aggregated data to the base station in a multi hop.

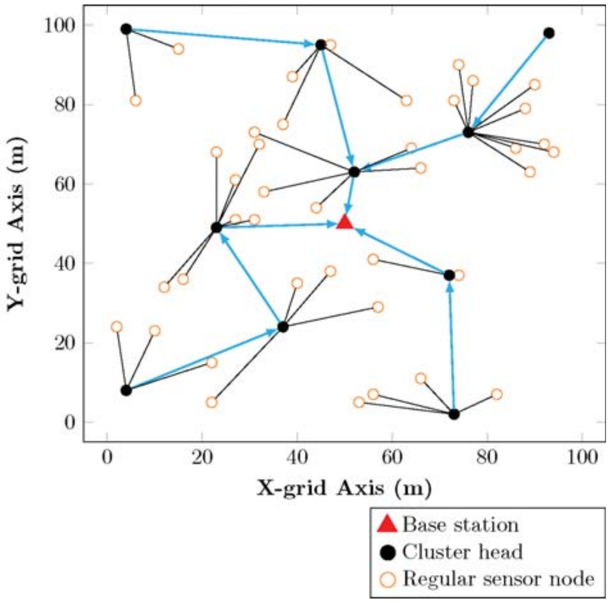

Figure 1. An example of network structure in HEED routing protocol.

With inter-cluster communication, the cluster heads which are far away from the base station choose a nearest neighbor cluster head and near the base station than itself to be a next-hop cluster head as shown in Fig. 1. The collected data is sent to the next-hop cluster head until reaches the base station. It makes the sensor nodes acted as a cluster head and located near the base station run out of battery fast because those nodes are responsible for aggregating sensor data from many sensor nodes and transmitting the data to the base station directly.

B. NHEED [9]

The NHEED routing protocol offers an improved multi-hop protocol based on HEED. In clustering process, the concept in NHEED is a slightly different from HEED by dealing with an isolated node, which is a cluster head without any sensor nodes joined. After clustering, the isolated nodes attempt to discover and join the nearest cluster head and become a member of the cluster. After that, for inter-cluster communication, each cluster head finds its neighborhood cluster heads within a broadcast radius. It then chooses an appropriate cluster head as its next hop to transmit the data by accounting residual energy and distance of each neighbor cluster head. Thus, the communication cost is computed as follow (2) [9].

$$\mathrm{cost}(i) = w\left(\frac{\sqrt{dist}}{d_{max}}\right) + (1-w)\left(\frac{E_{max}}{E_{re}}\right), \qquad i \in nbr \tag{2}$$

where nbr is a set of neighbor cluster heads which is near to the base station than itself, w is weighting factor to balance the distance to the cluster head and the residual energy of the cluster head, $dist$ is the distance between two cluster heads and d_{max} is the maximum distance among the neighbor cluster heads. Then, the next-hop cluster head can be selected by the following condition.

$$\mathrm{next\_hop}(i) = \begin{cases} BaseStation & dist\_sink(i) \le R_c \\ \min(\mathrm{cost}(i)) & dist\_sink(i) > R_c \end{cases} \tag{3}$$

where $dist\_sink(i)$ is the distance from node i to the base station. From above rule, the next hop of a cluster head is the base station if the base station is in the communication range (R_c) of this cluster head. Otherwise, the next hop of this cluster head is the cluster head with minimum cost among the neighbor cluster heads which are near to the base station than itself.

However, there are major problems emerged in NHEED protocol. The optimal value of communication range, i.e., R_c, is difficult to determine because of several network size. Furthermore, when no cluster heads with the range of R_c to the base station, other cluster heads must directly transmit the data to the base station by single hop with long distance. Consequently, the battery of those cluster heads is speedily drained.

III. Q-NHEED: PROPOSED MULTI-HOP ROUTING PROTOCOL

From the obstacles in NHEED for multi-hop model, quad-based routing protocol is proposed (named Q-NHEED) based on NHEED. The design algorithm of Q-NHEED is to select four cluster heads with near to the base station than others for multi-hop routing, instead of the determination of communication range (R_c) by proposed in NHEED. The selected cluster heads help balance the data transmission during network lifetime. There are two types of routing introduced in Q-NHEED, including intra-cluster routing and inter-cluster routing.

A. Intra-cluster Routing

An intra-cluster routing algorithm is the same as HEED and NHEED protocols, in which the highest residual energy and the lowest intra-cluster communication cost is the key criteria to select a cluster head. First, a desired percentage to impose the numbers of cluster head (C_{prob}) is initialized. Each node is set an initial probability of becoming a cluster head ($CH_{prob}(i)$) as see in (4).

$$CH_{prob}(i) = \max\left(C_{prob} \times \frac{E_{re}(i)}{E_{max}(i)}, p_{min}\right) \tag{4}$$

where $E_{re}(i)$ is the estimated current residual energy of sensor node i and $E_{max}(i)$ is the maximum energy of node i, corresponding to the energy of a fully re-charged battery.

Second, in repetition phase, each node finds a cluster head which it can transmit the data with minimum energy. The process in this phase is the same as that of HEED and NHEED. The sensor node with high energy is finished this phase before the sensor node with low energy. The sensor node with high energy is elected itself to be a cluster head and then broadcasts the message to the neighbor nodes within cluster radius. Other sensor nodes with low energy receive the message after the end of iteration and join the cluster according to the intra-cluster communication cost. Furthermore, Q-NHEED also deals with isolated nodes as same as NHEED. At the end of clustering, the cluster heads without sensor nodes joined are indicated to be an isolated node and join the nearest cluster, becoming the member of that cluster.

B. Inter-cluster Routing

Since the network area is large, if the sensor nodes which are far away from the base station transmit the data to the base station directly, they will consume a lot of battery power. Thus, the design algorithm for inter-cluster routing in Q-NHEED is that four cluster heads which are near to the base station is chosen. In Q-NHEED, there are two types of cluster heads, consisting of an advanced cluster head and an ordinary cluster head. The advanced cluster head refers to a set of four cluster heads which are near to the base station while the ordinary cluster head refers to a set of cluster heads which are not in the set of advanced cluster heads and definitely are far away from the base station.

For the ordinary cluster heads, let ordNbr(i) be a set of neighborhoods for the cluster head i which is near to the base station than node i. The cluster head i selects the next hop cluster head with a minimum cost from ordNbr(i). The inter-cluster communication cost for ordinary cluster head can be computed as follow:

$$\mathrm{cost}(i, j) = w\left(\frac{dist(i, j)}{d_{max}}\right) + (1-w)\left(\frac{E_{max}(j)}{E_{re}(j)}\right) \tag{5}$$

where w is the weighting factor to balance the distance and residual energy and $dist(i,j)$ is a distance between the cluster head i and the cluster head j and $j \in \text{ordNbr}(i)$.

The next hop of the ordinary cluster heads is selected as follow.

$$\text{next\_hop}(i) = \min(\text{cost}(i, j)), \qquad j \in \text{ordNbr}(i) \tag{6}$$

For the advanced cluster heads, each cluster head will make a decision to transmit the collected data to the base station directly or to another advanced cluster head with a minimum cost. Thus, the communication cost for the advanced cluster head to the base station is based both distance to base station and its residual energy, see as follow.

$$\text{cost}(i,bs) = w\left(\frac{dist(i,bs)}{d_{max}}\right) + (1-w)\left(\frac{E_{max}(i)}{E_{re}(i)}\right) \tag{7}$$

where $\text{cost}(i,bs)$ is a communication cost of node i for transmitting data to the base station directly and $dist(i,bs)$ is a distance between node i to the base station.

Let $\text{advNbr}(i)$ be the neighborhood advanced cluster head belonging to node i, which is near to the base station than node i. The communication cost for advanced cluster head to other advanced cluster heads can be applied (5) by considering $\text{advNbr}(i)$, instead of $\text{ordNbr}(i)$. The next hop for the advanced cluster head is chosen by the minimum cost of the cluster heads within $\text{advNbr}(i)$ comparing with the cost for transmitting to the base station directly, as following conditions.

$$\text{next\_hop}(i) = \min\begin{cases}\text{cost}(i, j) & j \in \text{advNbr}(i) \\ \text{cost}(i, bs) & \end{cases} \tag{8}$$

From above conditions, the next-hop of the advanced cluster head will be the base station if the cost to the base station is less than the minimum cost among other advanced cluster heads. Otherwise, one of advanced cluster heads is chosen as the next-hop cluster head.

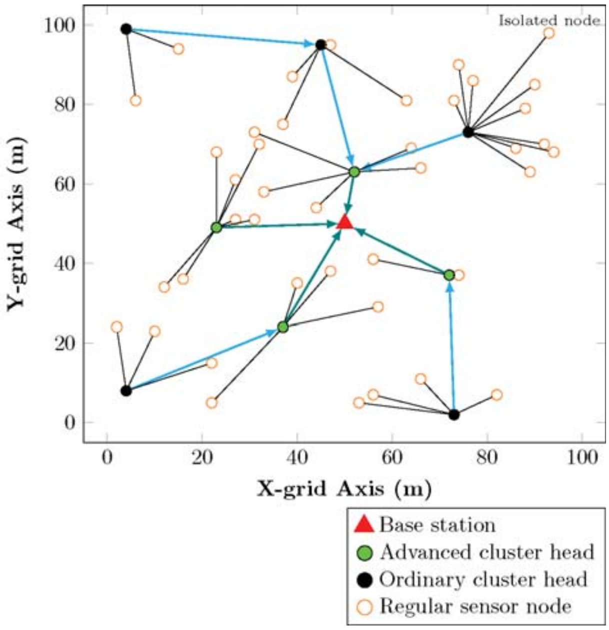

Figure 2. An example of network structure in Q-NHEED routing protocol.

Fig. 2 shows an example of network structure of Q-NHEED with multi-hop routing in both advanced cluster heads and ordinary cluster heads. Algorithm 1 shows the multi-hop routing algorithm for Q-NHEED and Table I describes notations used in the multi-hop routing algorithm for Q-NHEED.

TABLE I. NOTATIONS USED IN MULTI-HOP ROUTING ALGORITHM FOR Q-NHEED

Symbol	Description
bs	A base station
final_CH	A set of final cluster heads from the Clustering phase
ord_CH	A set of ordinary cluster heads
adv_CH	A set of advanced cluster heads
ordNbr(i)	A set of final cluster heads which are near to base station than the ordinary node i
advNbr(i)	A set of advanced cluster heads which are near to base station than the advanced node i
cost(i, j)	A communication cost between node i to j
min_cost	A minimum communication cost
next_hop(i)	A next hop cluster head of node i
find_neighbor(i,final_CH)	A function used to find neighbor cluster heads of node i corresponding to final_CH

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Algorithm 1 The multi-hop routing for Q-NHEED
Input: sensor node $i$, $i \in$ final_CH
Output: Next hop cluster head belonging to sensor node $i$
if $i$ is an ordinary cluster head then
    first ← TRUE
    ordNbr($i$) ← find_neighbor($i$, final_CH)
    for $j$ in ordNbr($i$) do
        if first then
            min_cost ← cost($i, j$)
            next_hop($i$) ← $j$
            first ← FALSE
        else
            if cost($i, j$) < min_cost then
                min_cost ← cost($i, j$)
                next_hop($i$) ← $j$
            end if
        end if
    end for
else if $i$ is an advanced cluster head then
    advNbr($i$) ← find_neighbor($i$, adv_CH)
    min_cost ← cost($i, bs$)
    next_hop($i$) ← $bs$
    for $j$ in advNbr($i$) do
        if cost($i, j$) < min_cost then
            min_cost ← cost($i, j$)
            next_hop($i$) ← $j$
        end if
    end for
end if
return next_hop($i$)
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IV. SIMULATION RESULTS

This section presents the simulation results by comparing the performance of the traditional HEED, NHEED and Q-NHEED routing protocols in terms of the percentage of dead nodes and the residual energy of network per round. The simulation parameters are listed in Table II.

TABLE II. SIMULATION PARAMETERS

Parameters	Values
Network size	100×100
Base station position	(50,50)
Number of nodes	100
Initial energy	0.5 J
Packet length	4,000 bits
Cluster probability (C_{prob})	0.05
Transmitter amplifier (E_{fs})	10 pJ/bit/m^2
Transmission circuit energy (E_{elec})	50 pJ/bit/m^2
Cluster radius	25 m
Communication Range (R_c)	50 m
Weighting factor	0.2

We experimented on 100 sensor nodes which are randomly distributed within 100×100 of a square network area. The base station is placed at the coordinate (50,50). The simulations were determined by the number of rounds when the number of nodes died ranged from 10% to 100%.

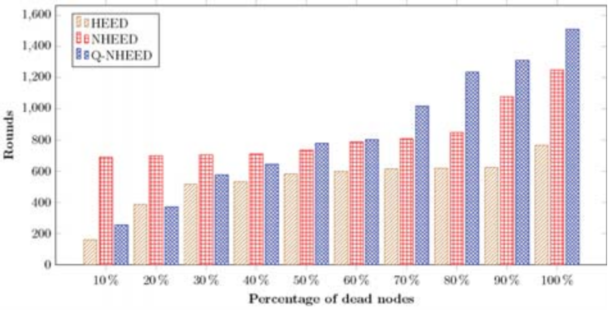

Figure 3. The percentage of dead nodes for three routing protocols.

Fig. 3 illustrates the number of dead nodes starting from 10% to 100% among the three routing protocols, traditional HEED, NHEED, and Q-NHEED. The result shows that the network life time in Q-NHEED is longer than that in the traditional HEED and NHEED measured by when all sensor nodes dead (100% of nodes dead). With the early rounds, the Q-NHEED is better than the traditional HEED, but it is worse than the NHEED protocol. With few rounds from starting, in NHEED, there are many cluster heads within R_c. Those nodes balance a workload to transmit to the base station, yields many sensor nodes is alive in NHEED. When time past, the number of cluster heads within R_c is decreased. The cluster heads where are outside R_c will transmit the collected data to the base station directly, which is an impact on the rapidly decreasing of their battery and is a dead node in consequence. It can be seen that the number of dead nodes in NHEED is rapidly decreased with few rounds. On the other hand, when the time past, the Q-NHEED selects four cluster heads which are near to the base station, no matter how far they are. Those cluster heads will help balance the network workload for transmitting to the base station during network lifetime, yields the extending number of alive nodes with more rounds.

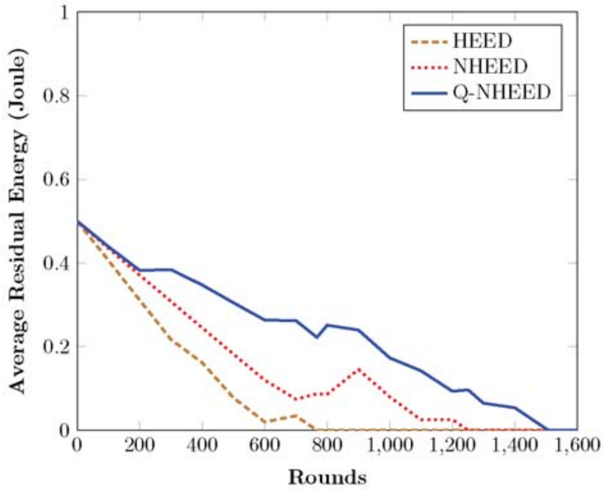

Figure 4. The comparison of average residual energy in network.

Fig. 4 confirms that the proposed protocol, Q-NHEED, outperforms the existing traditional HEED and NHEED in terms of the efficient usage energy, which is an impact on extending the network lifetime.

V. CONCLUSION

Wireless sensor networks are a major component of development in IoT technology. The main issue of wireless sensor networks is that the sensor nodes waste a lot of energy for transmitting the collected data to the base station directly. In this paper, an improved hierarchical routing protocol with multi-hop routing, named Q-NHEED, is proposed to provide an efficient energy consumption and extend a lifetime of wireless sensor networks. Our simulation results show that the proposed routing protocol gives a prolonged lifetime of network and outperforms the traditional HEED and NHEED in points of view energy consumption of sensor nodes during use. In our future work, other factors, i.e., node degree, will be comprehensively studied for inter-cluster routing selection to improve the network lifetime and also extend the longer period by measuring the first node died.

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