Energy-Efficient Protocol for Multi-hop Sensor Networks

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Abstract: Among the main problems which remains to be addressed in wireless sensor networks (WSNs), the energy-efficiency and the lifetime of these networks, particularly those that are deployed over large areas, are two of the most important one. The hierarchical routing protocols are playing a key role in reducing energy consumption in WSN and, for most of these protocols, the cluster-head (CH) is also used as a relay node to transmit data to the base station. This is inefficient since they consume more energy than the other nodes of the networks. This paper reports on a new algorithm, named multi-hop energy-efficient (MHEE), which maximizes the lifetime of the network. It is based on a reliable selection mechanism for the relay nodes between the cluster heads (CH) and the base station in order to share evenly the energy consumption amongst the nodes of the networks. The results obtained show that the proposed protocol exceeds the performance existing representatives WSN routing protocols.

Key words: Wireless sensor networks, multi-hop, routing protocol, energy efficient, clustering, network lifetime.

1. Introduction

A wireless sensor networks (WSNs) is comprised of spatially distributed sensor nodes, where each one of them contains units for sensing, processing, and communicating data packet. This is done with many other nodes acting as relays before reaching final destination and the wireless transmission uses more energy than data processing. In general, each sensor node is both a sensor and a router, and its computing ability, storage capacity, communication ability and power supply are limited. Typically, these nodes report sensed data to a base station for further processing. They are equipped with low-cost small-capacity batteries which are, in most cases, non-rechargeable and irreplaceable. Therefore, the energy efficiency plays an important in the WSN to extend the network lifetime [1], [2].

Many routing protocols have been proposed to reduce the energy consumption between nodes for efficient data transmission, but their implementation in large network is still a problem because they do not achieve the expected lifetime required by the industrial applications [3]. Thus, each routing protocol has specific features depending on the application and the network architecture to improve the optimum energy efficiency; these characteristics are being designed using localization and clustering of the data, a well-known technique for increasing network lifetime, improve energy efficiency and equilibrate energy consumption amongst the nodes [4].

The clustering protocols are mainly considered as cross-layering techniques for designing energy efficient hierarchical wireless sensor networks. The basic principle of the protocol is to organize the sensor nodes into groups called clusters. In each cluster, a node is selected as the cluster-head. Instead of sending data directly to the base station, each node sends data to their corresponding CH. Once the CH has received

the data of all nodes in clusters, it realizes the fusion and compression of data and communicates with the base station via single or multi-hop [5].

The communication model that WSN uses is either single-hop or multi-hop [6]-[9]. Since energy consumption in wireless systems is directly proportional of the square of the distance, single-hop communication is expensive in terms of energy consumption. Most of the routing algorithms use multi-hop communication model since it is more energy efficient in terms of energy consumption. However, with multi hop communication causes energy unbalancing, because the nodes in proximity of the base station play the role of relay node for data transmission which causes depleting the energy quickly. This greatly affect the network lifetime.

2. Current Knowledge

Different methods for clustering the data routing are available in the public literature and a very brief review of these as well as a useful comparison to establish their respective potential are given below:

2.1. Low Energy Adaptive Clustering (LEACH)

This protocol is one of the first hierarchical routing protocols used in WSN to increase the network lifetime. In LEACH, the nodes organize themselves into local cluster; each cluster is formed of CH node and another nodes. The CH can be selected randomly and then rotate this role to evenly distribute the energy load among the sensors in the network [7], [8].

The operation of LEACH is divided into rounds, each round having two phases; a set-up phase when the clusters are organized and a steady-state phase when the nodes are transmitting the data to their respective CH which, in turn, transmit the whole set of compressed data to the base station.

During the set-up phase, each sensor node choose a random number between 0 and 1. If this number is below the threshold $T(n)$ as indicated by eq.(1), the node will broadcast itself as being the CH. The non-CH nodes choose the CH with greater signal strength and join the cluster.

$$T(n) = \begin{cases} \dfrac{P}{1 - P \times \left(r \bmod \dfrac{1}{P} \right)} & \text{if } n \in G \\ 0 & \text{if not} \end{cases} \tag{1}$$

where G is the set of nodes that did not become CHs in the last N/k rounds, k is the number of expected CHs, N is the total number of nodes, P is the percentage of the number of CHs is selected equal to k/N and r is the current number of round.

In the steady-state phase, data are transferred from the non-CHs nodes to the CH and on to the base station. After a certain period of time, set-up phase will start again.

2.2. Two Level LEACH (TL-LEACH)

The TL-LEACH [8] is an extension of LEACH protocol. In this protocol, the cluster-heads can be decomposed in two-level, primary and secondary. The secondary CH's collects data from the primary CH's member, and relays the data to the base station. The structure of two levels reduces the number of nodes when data is transmitted from source to the base station and reducing total energy consumption.

2.3. Energy Efficient Clustering Hierarchy (EECH)

EECH protocol [8] uses an energy based threshold calculation to elect CHs in the network, in which there is a higher probability for a node with more energy to be selected as CH than a node with less energy. It uses

multi-hop communication between a CH and the BS to reduce energy consumption in the network.

2.4. Multi-hop Routing LEACH (MR-LEACH)

In the MR-LEACH [9], the network divided in optimal number of layer, the BS is involved in the selection of the CH and it publishes a Time Division Multiple Access (TDMA) schedule for each CHs layer. Based on this schedule, each CHs layer collaborates with the adjacent CHs layers to transmit sensor's data to the BS with multi-hop routing.

2.5. Improved LEACH (ILEACH)

The ILEACH protocol [10] uses the residual energy of the nodes to select the CH, preventing the nodes with weak energy to become CH. An energy management function to equilibrate the energy consumption between the CHs has been proposed and a data aggregation tree is designed to send data CH to the BS in multi-hop mode.

Table 1 summarizes the advantages and disadvantages of these different protocols.

Table 1. Comparison of Routing Protocols

Protocol	Advantages	Disadvantages
LEACH	Reduce the total data transmitted to the base station	Cannot be applied in networks deployed in large regions.
TL LEACH	The number of nodes transmitting to the base station is reduced ,therefore diminish the total energy consumption	Similarly, this does not apply for networks deployed over large areas.
EECH	Energy consumption is well distributed on all nodes for small networks.	For large networks, uneven distribution of nodes energy.
MR-LEACH	Decomposition of nodes network into multi-levels.	Centralized routing protocol.
ILEACH	Diminution of the communication distance between the CHs and the BS.	Fast energy consumption for the nodes closer to the BS.

3. Network and Energy Consumption Model Used in Our Study

A sensor field consisting of N sensors deployed randomly in a rectangular space is considered. Our node network model has the following properties:
- The base station is located far away from the node network.
- All nodes are equally capable of becoming CHs.
- All the nodes are homogeneous and each node is assigned with a distinctive identifier (ID).
- Sensor nodes are aware of their location or position in the network.
- All nodes are capable of sending data to the base station.
- The base station and the nodes are stationary after deployment.

For the protocol analysis, a simple model (Fig. 1) of communication energy dissipation is used where the transmitter and the receiver are using energy to power the electronic devices and the power amplifier.
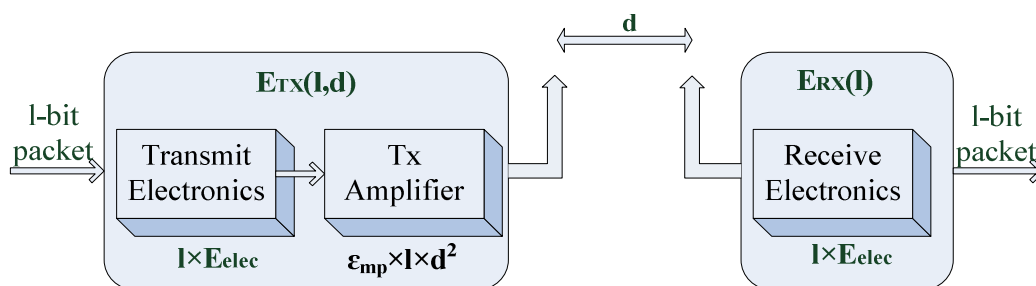

Fig. 1. Simple energy dissipation model.

Depending upon the distance between the transmitter and the receiver, a typical energy consumption model is adopted, both free space and multipath fading channel models are proportional to d^2 and in d^4 power loss are used. If the distance is below a threshold d_0, the free space (*fs*) model is used; on the contrary, multipath propagation model is used. Therefore, to transmit *l*-bit packet over a distance *d*, the required energy is given by the following equations [7]:

$$E_{TX}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & \text{if } d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4 & \text{if } d \geq d_0 \end{cases}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$$

$$(2)$$

where E_{elec} is the energy consumption per bit in the transmitter and receiver circuitry [7], d_0 is the maximum distance for which the transmission factors change values, ε_{fs} is the free space model's amplifier energy consumption, and ε_{mp} is the multiple attenuation model amplifier energy consumption .

The energy consumed to receive *l*-bit data is represented in (3):

$$E_{RX}(l,d) = lE_{elec}$$

$$(3)$$

4. The Proposed Protocol

In the clustering protocol, the CH is receiving all the nodes data and merges them in a single packet before sending it to the base station. The energy consumption in each cluster is proportional to the surface of the cluster since in large size clusters the distance between the CH and the member nodes increases.

After all the data have been received, the CH transmits the packet to the base station from a relay node to diminish the separation distance between the CH and the base station. For the large surfaces, two mechanisms are available; in the first mechanism, the clusters number are increase therefore increasing the inter-cluster energy consumption and ,in the second mechanism, the number of clusters is diminished, yielding a diminution of the inter-cluster energy consumption and an increase of intra-cluster energy consumption.

In the clustering protocols briefly covered in Section 2, the CHs closer to the base station are also playing the role of nodes at the same time and this is not optimal for two reasons. First, when the base station is far from the node network, it is preferable to diminish the transmission distance by choosing closer nodes such as relay nodes. When this role is attributed to the CHs such as in these protocols, this leads to the rapid depletion of their energy and it is more difficult to use them as relay nodes, leading to a shorter operational lifetime for the network. The second reason is that when a node is transmitting and receiving at the same time, it consumes of course more energy than if it just transmits or receives. Therefore, when two tasks are attributed to the same nodes, particularly closer to the end of the lifetime of the network, could lead to total energy exhaustion.

Using these considerations, it can therefore be concluded that there are two main problems to be dealt with, namely the cluster surface and the relay nodes. To address these issues, our new approach proposes to devise the network surface in two or more levels and elect a relay node for each of these levels. It differs from most of the known protocols that are based on the distance to the base station and the nodes energy level. Our objective is to have uniform energy consumption between all the nodes of the network.

Our protocol, named MHEE (multi-hop energy efficient) is divided into three phases, A) the identification and clustering, B) the relay nodes election and C) the data routing.

4.1. Identification and Clustering

This phase has two steps, namely the identification of the nodes as a function of the levels and the CHs election and the nodes clustering.

4.1.1. Identification

The networks dedicated to the coverage of large surfaces lose more energy when transmitting data between the CHs and the base station. To diminish the energy consummation between the network nodes, it is divided into two or more levels. Fig. 2 shows the result for two levels (1&2).

When the distribution of the nodes in the surveillance zone is accomplished, each node has the information concerning its coordinates (x_i, y_i), as well as the length and the width of the total zone. If the ordinate y_i of node i is larger than half the length of the zone, then node i is at level 2, the level closer to the base station. Conversely, if it is smaller, then node i belongs to level 1, the more remote level from the base station.

4.1.2. Clustering

When each level has been determined, the CHs election is done using the $T(n)$ level concept of eq. (1) of Section 2. Then each elected CH broadcasts an advertisement message to the rest of the nodes that belongs to the same level to invite them to joint their clusters and each one will join the closer CH. Thereafter, each CH creates a TDMA schedule for each node in its cluster. This procedure is conceptually pictured in Fig. 2.
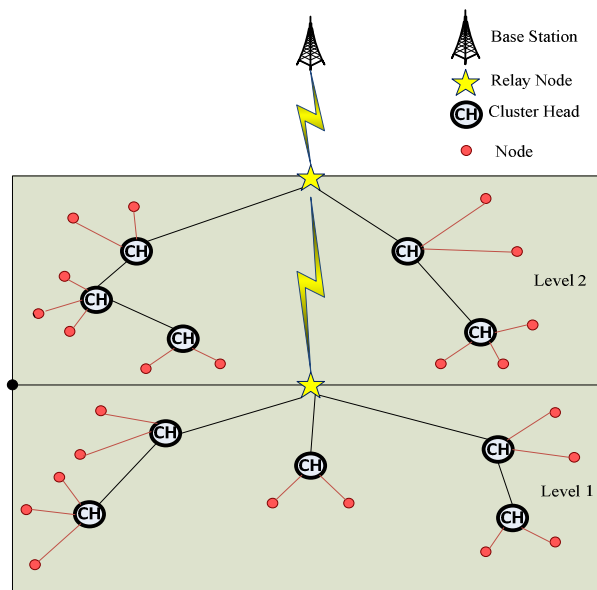

Fig. 2. MHEE protocol.

4.2. Relay Nodes Election

The distribution of energy between the nodes of the network permits to extend the network lifetime. For an equitable share of energy consumption between the network nodes, a relay node is elected for each level and its characteristics are: a maximum energy level and a minimum distance with the base station. This node receives all the data from the same level CHs and, after, N_{r1} (the relay node of level 1) send the data to relay node of level 2. Once all the data has been received by N_{r2}, it transmits it directly to the base station.

The election of a relay node at level 1 is based on threshold TH$_1$, as shown in eq. (4) below. For each level,

each CH knows the position of all the other CHs. The closer CH from the base station will broadcast a message to all the nodes in order to know their TH_1 and their identification. With the reception of all node thresholds, the node with the larger TH_1 will be elected by the CH as the level 1 relay node and will broadcast an advertisement message containing the identifier of N_{r1} to all the CHs of that level. This is expressed in eq. (4)

$$TH_{i1} = \frac{E_i}{E_0} + \frac{d_{max1}}{d_{i\_To\_BS}} \tag{4}$$

With TH_{i1} representing the threshold of the node i for level 1, E_i the residual energy of node i, E_0 the initial energy of the node, d_{max1} the maximum distance between the surveillance zone of level 1 (as expressed in eq. 5) and the base station and $d_{i\_To\_BS}$ the distance between node i and the base station. This is depicted in Fig. 3.

$$d_{max1} = \sqrt{(x_{BS})^2 + (y_{BS})^2} \tag{5}$$

The same phenomenon will occur at level 2 and will be expressed in eq. (6).

$$TH_{i2} = \frac{E_i}{E_0} + \frac{d_{max2}}{d_{i\_To\_BS}} \tag{6}$$

where TH_{i2} representing the threshold of the node i for level 2, d_{max2} is the maximum distance between the surveillance zone of level 2 and the base station (eq. 7).

$$d_{max2} = \sqrt{(x_{BS})^2 + \left((y_{BS}) - \left(\frac{y_{surface}}{2}\right)\right)^2} \tag{7}$$

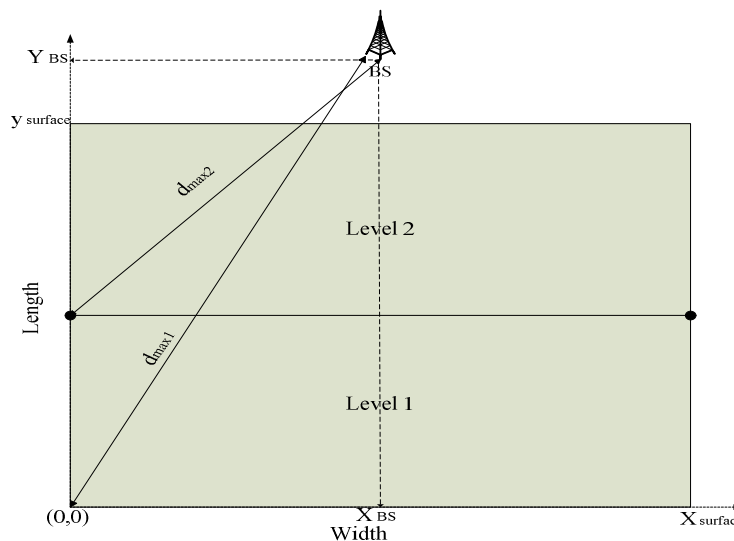where $y_{surface}$ is the width of the node network surface.

Fig. 3. Network surface for MHEE protocol.

4.3. Data Routing

When the clusters are configured, the CHs are elected and the relay nodes of each level are spotted, the data routing phase to the base station begins.

In this paper, a multi-hop data communication algorithm between the CHs is propose in order to minimize the distance between CH and the energy consumption during transmission in each level where a CH will communicate with the closer CH in order to send the data to the corresponding relay node.

5. Simulation Results

Before experimentation in a real system, various clustering protocols scenarios were simulated using MATLAB. The values of the parameters used in the simulation are given in Table 2.

Table 2. Parameters Used in Simulation

Parameter	Value
Area of network	(300m, 300m)
Number of nodes	300
Situation of base station	(150m, 400m)
Packet Size	4000 bits
Eo: Initial Energy of Sensor Nodes	1 J
do: Threshold distance	87 m
Efs: Transmit amplifier free-space	10 pJ/bit/m2
Eamp: Transmit amplifier for two-way	0.0013 pJ/bit/m4
Eelec: Transceiver idle state energy consumption	50 nJ/bit
EDA: Consume Energy Data Aggregation	5 nJ/bit
Popt: Probability of optimum CH	10%

Fig. 4 illustrates the comparison between LEACH, ILEACH, MR-LEACH protocol and MHEE protocol in term of the lifetime per round. It clearly shows that our proposed protocol MHEE is more stable than the others since the degeneration begins later than the other algorithms.

While comparing our algorithm with the other ones, it has been noticed that the base station, when using our MHEE protocol, received information from the surveillance zone over a longer period of time.
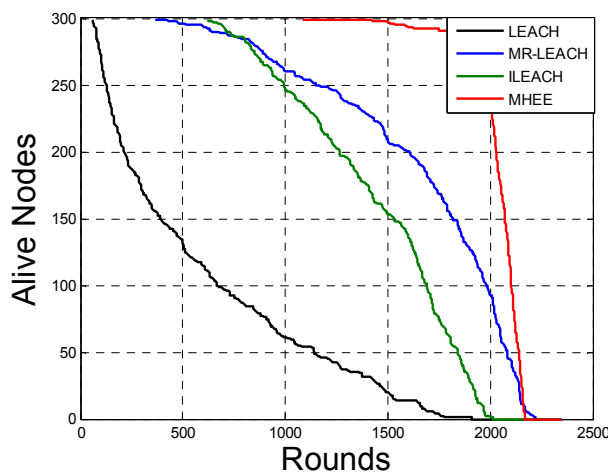

Fig. 4. Network lifetime comparison amongst LEACH, ILEACH, MR-LEACH and MHEE.

The amount of data received by each algorithm considered is shown in Fig. 5 and this result shows an increase in the amount of data received by the base station using the MHEE protocol of 74,4%, 29 % and 19,4% in regard to LEACH, ILEACH and MR-LEACH respectively.
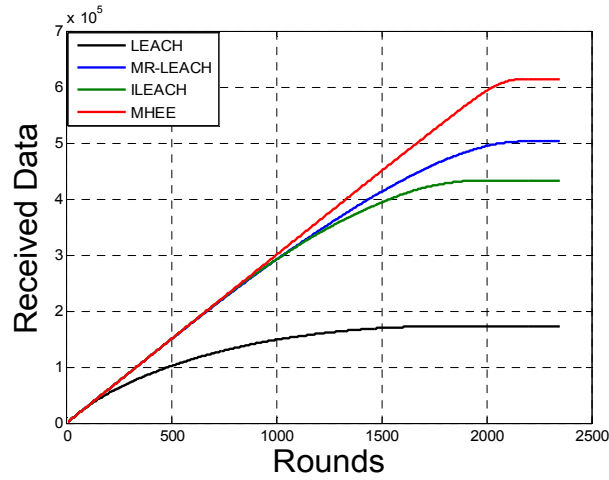
Fig. 5. The data received by the base station by round.

Fig. 6 depicts the remaining energy in the whole network for each round. This result shows clearly that the distribution of energy in the MHEE protocol driven network is above the others while being almost linear the full number of rounds.
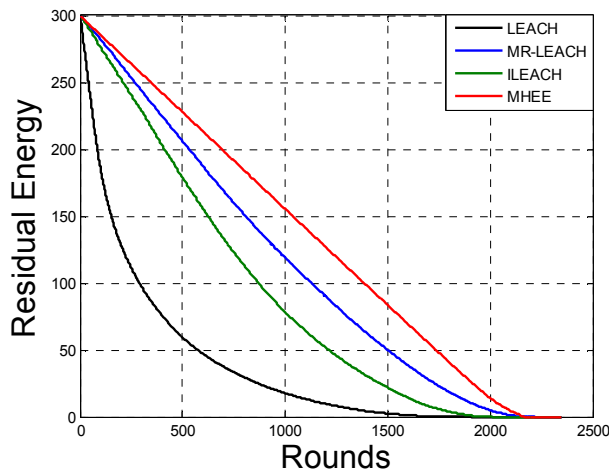

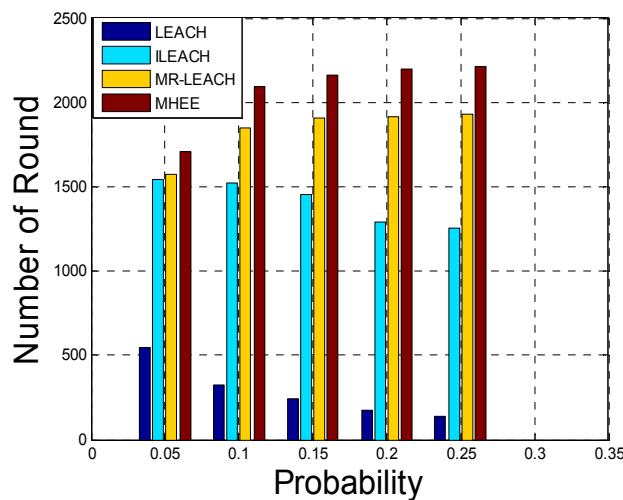Fig. 6. Energy consumption of the WSN for each round.

Fig. 7. The HDN for different probability of CH in the network.

Fig. 7 is another result showing comparative advantages for our MHEE protocol. In this case, the probability of HDN (half dead nodes) is illustrated for different numbers of CHs in the network. For two protocols, MHEE and MR-LEACH, the more the probability of nodes is increased, the more the lifetime of HDN are increased.

Many other results will be presented and discuss at the conference.

6. Conclusion

This paper is proposing a novel clustering algorithm specially designed for large coverage network. The MHEE protocol divides the nodes network in two or more levels and, at each of these levels, a relay node is selected. The usefulness of this node is to distribute the energy consumption between nodes in order to increase the amount of received information. Subsequently, a multi-hop communication between the CHs is used to transmit the data to the relay node and the base station.

The proposed protocol permits to reduce the inter-cluster communication and consequently to diminish the energy consumption. Simulation results show an increase of the data received by the base station and a better distribution of the energy consumption compared to other existing protocols such LEACH, ILEACH and MR-LEACH.

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