Position-Based Clustering: An Energy-Efficient Clustering Hierarchy for Heterogeneous Wireless Sensor Networks

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Abstract: ***A clustering algorithm is a key technique used to increase the scalability and lifetime of the Wireless Sensor Networks (WSNs). In this paper, we propose and evaluate a distributed energy-efficient clustering algorithm for heterogeneous WSNs, which is called Position-Based Clustering (PBC). This protocol is an improvement of LEACH-E. In PBC, the cluster-heads are elected by using probabilities based on the ratio between residual energy of each node and the remaining energy of the network. It uses a 2-level hierarchy by selecting an intermediate cluster head for data transmission. Moreover, it uses a new technique for cluster formation based not only on the received signal strength of the cluster head's advertisement but also on its position. Simulations show that the proposed algorithm increases the lifetime of the whole network and performs better than LEACH, LEACH-E and SEP.***

Keywords: Wireless Sensor Networks, Clustering Algorithm, Heterogeneous Environment, Energy-Efficient.

I. Introduction

Owing to the advances of Micro-Electro-Mechanical Systems (MEMS) and wireless communication, Wireless Sensor Networks (WSNs) have become an indispensable tool to carry out many applications impossible for other types of networks [1, 2]. A WSN is composed of a large number of sensor nodes that are often deployed in ad hoc manner in hostile environment. Clustering technique is used to increase the lifetime of WSNs [3, 4]. In fact, only some nodes are required to transmit data over a long distance and the rest will need to complete short distance transmission only.

In [5], it is proposed to elect the cluster-heads according to the energy left in each node. In [6], this clustering protocol is called LEACH-E. Based on LEACH-E protocol, we develop and validate a newer algorithm called Position-Based Clustering (PBC). This protocol is proposed to increase the whole network lifetime on a heterogeneous WSN with a Base Station (BS) located far away from the sensor area. PBC introduces the 2-level hierarchy concept based on the maximum of the ratio between residual energy and the distance to the BS of each Cluster Head (CH). Moreover, it introduces a new technique for cluster formation based not only on the received signal strength of the advertisement of CH but also on its position. Thus, these improvements permit a better distribution of the energy load through the sensors in the WSN.

The remainder of this paper is organized as follows. Section II presents the related work. Section III introduces some preliminary notions concerning the proposed protocol. Section IV exhibits the details and analyzes the properties of PBC. Section V evaluates the performance of PBC by simulations and compares it with LEACH, LEACH-E and SEP. Finally, Section VI gives concluding remarks.

II. Related work

The routing protocols for WSNs can be categorized as follow: the clustering algorithms applied in homogeneous networks are called homogeneous schemes, where all nodes have the same initial energy, such as LEACH [4]; and the clustering algorithms applied in heterogeneous networks are referred to as heterogeneous clustering schemes, where all the nodes of the sensor network are equipped with different amount of energy, such as SEP [7], EECS [8], DEEC [6], and [9]. SEP is developed for the two-level heterogeneous networks, the advance nodes and normal nodes. However, SEP performs poorly in multi-level heterogeneous wireless networks and when heterogeneity is a result of operation of the sensor network. The EECS protocol elects the cluster-heads with more residual energy through local radio communication. The DEEC protocol is a distributed energy-efficient clustering scheme for heterogeneous wireless sensor networks, in which the cluster-heads are elected by a probability based on the ratio between residual energy of each node and the average energy of the network. In DEEC protocol, the BS is located in the center of the sensing area and uses 1-level hierarchy concept. In [5], a protocol is proposed to elect the cluster-heads according to the energy left in each node. This protocol is called LEACH-E in [6]. The drawbacks of LEACH-E are that it requires the assistance of routing protocol, which should allow each node to know the total energy of network, it utilizes direct transmission from a cluster heads to the BS and it uses only the received signal strength of the advertisement in cluster formation process; the disadvantage of this strategy is that it could forced nodes to choose the cluster heads which have greater distance from the BS than the nodes themselves.

Our work is inspired by the previous approaches, but it differs by introducing to LEACH-E an adapted formula to estimate the network lifetime and the total energy dissipated in the network during each round, thus avoiding the need of assistance by routing protocol. Since we assume that the BS is far away from the sensing area, we are using 2-level hierarchy concept for transmitting data to the BS. Also, by using the position of CHs in cluster formation process, nodes will send their data in effective paths, and do not send their data to the outer place.

III. Preliminaries

A. Heterogeneous WSN model

In this study, we describe the network model. Assume that there are N sensor nodes, which are uniformly dispersed within a M x M square region (Fig. 3). The nodes always have data to transmit to a BS, which is often far from the sensing area. This kind of sensor network can be used to track the military object or monitor remote environment. The network is organized into a clustering hierarchy, and the cluster-heads execute fusion function to reduce redundant data produced by the sensor nodes within the clusters. The cluster-heads transmit the aggregated data to the BS. We assume that the nodes are stationary as supposed in [4]. In the two-level heterogeneous networks, there are two types of sensor nodes, i.e., the advanced nodes and normal nodes. We denote by E_0 the initial energy of the normal nodes, and m the fraction of the advanced nodes, which own a times more energy than the normal ones. Thus, there are Nm advanced nodes equipped with an initial energy of $E_0(1+a)$, and N (1−m) normal nodes equipped with an initial energy of E_0. The total initial energy of the two-level heterogeneous networks is given by:

$$E_{total} = N(1-m)\,E_0 + NmE_0(1+a) = NE_0(1+am)$$

B. Radio energy dissipation model

We use the same radio model as stated in [10] with E_{elec} as the energy being dissipated to run the transmitter or receiver circuitry to transmit or receive one bit of the data packet and ε_{amp} as the energy dissipation of the transmission amplifier to convey one bit of the data packet through the channel with length d to the destined node (Figure 1).

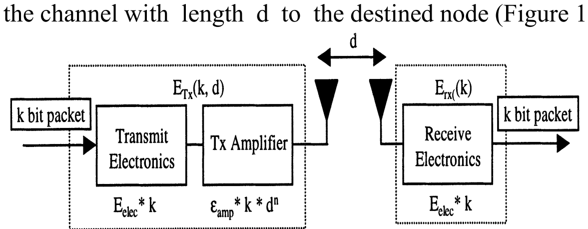

Figure 1. Radio energy dissipation model.

Transmission (E_{Tx}) and receiving (E_{rx}) costs are calculated as follows:

$$E_{Tx}(l,d) = lE_{elec} + l\varepsilon_{amp}d^n$$
$$E_{rx}(l) = lE_{elec}$$

with l as the length of the transmitted/received message in bits, d as the distance between transmitter and receiver Node and d as the path loss exponent which is two for the free space model and can be up to six depending on the environment and network topology [10].

As it can be seen, the transmitter expends energy to run the radio electronics and power amplifier, while the receiver only expends energy to run the radio electronics.

In this paper the free space model ($n = 2$, $\varepsilon_{amp} = \varepsilon_{fs}$) is used for the transmission distances below a threshold distance d_0 with typical value of 87.7 m, and multipath model ($n = 4$, $\varepsilon_{amp} = \varepsilon_{mp}$) is used for further distances.

In cluster-based schemes, the cluster heads are responsible for aggregating their cluster members' data signals to produce a single representative signal, expending lE_{DA} for each l-bit input signal, where E_{DA} is the energy for data aggregation and is set to 5 nJ/bit/signal.

IV. Our extension proposed: the PBC protocol.

In Cluster formation of LEACH-E, each node that has elected itself a cluster-head for the current round broadcasts an advertisement message to the rest of the nodes. The non-cluster-head nodes (NCH) must keep their receivers on during this phase of set-up to hear the advertisements of all the cluster-head nodes. After this phase is complete, each non-cluster-head node decides the cluster to which it will belong for this round. This decision is based on the received signal strength of the advertisement. The cluster-head advertisement heard with the largest signal strength is the cluster-head to whom the minimum amount of transmitted energy is needed for communication. As a result, the non-cluster-head nodes might send their data to the further place and afterwards their data travels back a long haul distance to reach the BS. These kinds of transmissions waste the energy resources of the network. To save energy, we divided the set of CHs in each round, for each non-cluster-head node NCH, into two classes: Front_CHs and Back_CHs.

Front_CHs is defined as CHs in front the NCH in the direction of the BS; and, Back_CHs is defined as CHs in the back of the NCH in the opposite BS direction.

If Front_CHs is empty, NCH chooses the cluster to which it will belong in Back_CHs, according to received signal strength of the advertisement.

If Front_CHs is not empty, NCH computes the nearest CH from Front_CHs (nearestFrontCH), according to received signal strength of the advertisement, and computes the distance between itself, nearsetFrontCH and BS (NCH-nearsetFrontCH-BS). If Back_CHs is empty, NCH chooses nearsetFrontCH as his cluster head. Else (i.e. Back_CHs is not empty) NCH computes the nearest CH from Back_CHs (nearestBackCH), according to received signal strength of the advertisement, and computes the distance between itself, nearsetBackCH and BS (NCH-nearsetBackCH-BS); also NCH compares NCH-nearsetFrontCH-BS and NCH-nearsetBackCH-BS: if NCH-nearsetFrontCH-BS is greater than NCH-nearsetBackCH-BS then NCH chooses nearestBackCH as his cluster head otherwise NCH chooses nearestFrontCH. By this strategy, almost nodes will transmit their data in the direction of the BS and then saving energy. In fact, nodes will send their data in effective paths, and do not send their data to the outer place. Simulation in Fig. 3 illustrates this strategy.

In PBC, the probability threshold, that each node s_i uses to determine whether itself to become a cluster-head in each round, is given as follow [6]:

$$T(s_i) = \begin{cases} \frac{p_i}{1-p_i(r \bmod \frac{1}{p_i})} & if \quad s_i \in G \\ 0 & otherwise \end{cases} \qquad (1)$$

where G is the set of nodes that are eligible to be cluster heads at round r. In each round r, when node s_i finds it is eligible to be a cluster head, it will choose a random number between 0 and 1. If the number is less than threshold $T(s_i)$, the node s_i becomes a cluster head during the current round. Also, p_i is defined as follow [5]:

$$p_i(r) = min\left\{\frac{E_i(r)}{E_{total}(r)}k, 1\right\} \quad (2)$$

where $E_i(r)$ is the current energy of node i, k is the desired number of cluster, and $E_{total}(r)$ is an estimate of the remaining energy of the network per round r:

$$E_{total}(r) = E_{total}\left(1 - \frac{r}{R}\right) \quad (3)$$

where R denotes the total rounds of the network lifetime and E_{total} the total initial energy of the two-level heterogeneous WSN (see 3.1). The value of R is:

$$R = \frac{E_{total}}{E_{Round}} \quad (4)$$

where E_{Round}, denotes the total energy dissipated in the network during a round r, is given by:

$$E_{Round} = L\left[2NE_{elec} + NE_{DA} + (k-1)\epsilon_{mp}d^4_{toMax\_RatCH} + N\epsilon_{fs}d^2_{toCH} + E\epsilon_{mp}d^4_{toBS}\right] \quad (5)$$

where k is the number of clusters, E_{DA} is the data aggregation cost expended in the cluster-heads, d_{toBS} is the average distance between the cluster-head and the BS, d_{toMax_RatCH} is the average distance between the cluster-heads and the Max_RatCH, which is the CH that has the maximum ratio between residual energy and the distance to the BS of each CHs, d_{toCH} is the average distance between the cluster members and the cluster-head. Assuming that the nodes are uniformly distributed and by using the result in [5, 11], we can get the equations as follow:

$$d_{toCH} = \frac{M}{\sqrt{2k\pi}} \quad (6)$$

$$d_{toMax\_RatCH} = \frac{1}{M^2}\iint\sqrt{(x_i + x_j)^2 + (y_i + y_j)^2}\,dxdy \approx \frac{M}{2} \quad (7)$$

$$d_{toBS} = \sqrt{2\pi}\,\frac{M}{2} \quad (8)$$

$$k = \frac{\sqrt{E_{fs}}}{\sqrt{E_{mp}}}\frac{\sqrt{N}}{\sqrt{2\pi}}\frac{M}{d^2_{toMax\_RatCH}} \quad (9)$$

Substituting equations (9, 8, 7, 6, 5, 4, 3, and 2) into equation (1), we obtain the probability threshold. In PBC, every sensor node independently elects itself as a cluster-head based on its initial energy and residual energy. To control the energy expenditure of nodes by means of adaptive approach, PBC uses the average energy of the network as the reference energy. Thus, PBC does not require any global knowledge of energy at every election round and the need of assistance by routing protocol.

In data transmission of LEACH-E, since the BS is located far away from the network, the total network energy consumption in each transmission to the BS will be very important; because communication is more expensive than computational in term of energy cost. To optimize the energy dissipated in the network, our PBC introduces 2-level hierarchy concept which allows a better use of the energy consumed in the network. In fact, based on the information coordinates and the residual energy included on the message broadcasted, the CHs elected can select one of them which has the Maximum of the Ratio between residual energy and the distance to the BS. We called this intermediate Cluster Head as Max_RatCH. The ratio can be seen as tradeoff between residual energy and nearness to the BS. The Max_RatCH collects data coming from CHs, compress it into a single signal and send it directly to the BS. Each non cluster heads (NCH) sends its data during their allocated transmission time (TDMA) to the respective cluster head. The CH node must keep its receiver on in order to receive all the data from the nodes in the cluster. When all the data is received, the cluster head node performs signal processing functions to compress the data into a single signal. When this phase is completed, each cluster head can send the aggregated data to the Max_RatCH. Data transmition algorithm of PBC can be summarized as in figure Fig 2.

Figure 2. Algorithm

```
For each node i
    If (node i is NCH) then
      Appropriate CH election (see IV §.1. cluster formation)
      Send data to CH
    Else
        If (node i is not Max_RatCH) then
            Data aggregation(nodes)
              If (dtoBS>dtoMax_RatCH) then
                  Send to Max_RatCH
             Else
                    Send to BS
            End if
        Else
              First data aggregation (nodes)
              Second data aggregation (CHs)
              Send to BS
        End if
    End if
End for
```

NCH: not a CH.
CH : Cluster head
dtoBS : distance to the BS.
dtoMax_RatCH : distance to Max_RatCH
Max_RatCH : the CH with the maximum report between residual energy and dtoBS

TABLE I
Radio characteristics used in our simulations

Parameter	Value
E_{elec}	5 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_0	0.5 J
E_{DA}	5 nJ/bit/message
d_0	87,7 m
Message size	4000 bits
p_{opt}	0.1

V. Simulation Results

We consider a WSN with N = 100 nodes randomly distributed in a 100m_100m sensing area (Fig. 3). We assume the BS is far away from the sensing region and placed at location (x = 50; y = 175). The radio parameters used in our simulations are shown in Table 1. We assume that all nodes know their location coordinates. We use in this study a similar energy model as proposed in [10]. We will consider the following scenarios and examine several performance measures.

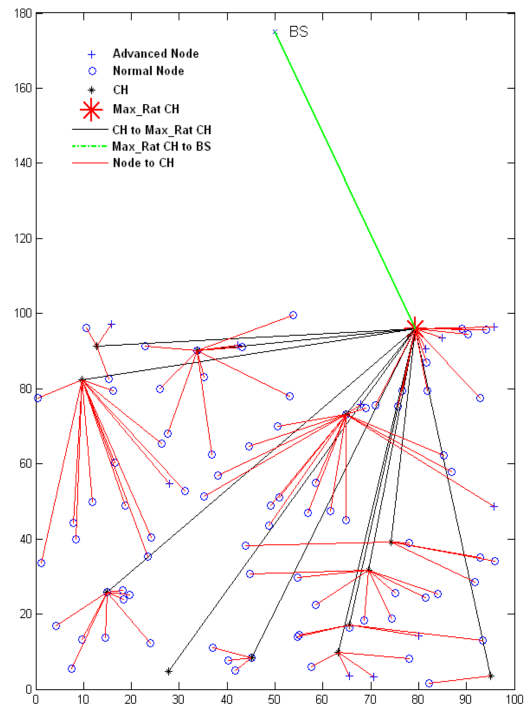

Figure 3. A random network with 100 node; the BS is outside.

First, we observe the performance of LEACH, LEACH-E, SEP and PBC under two kinds of 2-level heterogeneous networks. Fig. 4 shows the results of the case with m = 0.1 and a = 5. It is obvious that the stable time of PBC is prolonged compared to that of LEACH, SEP and LEACH-E.

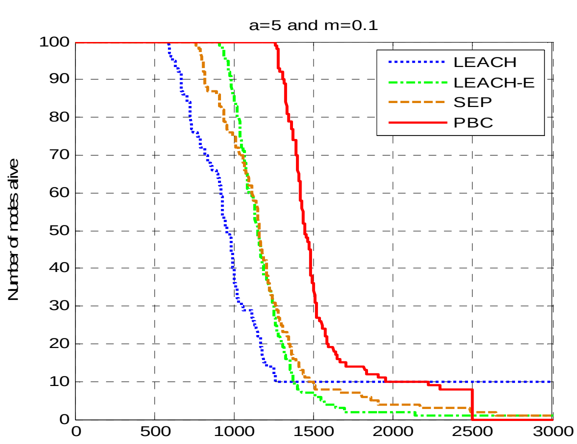

Figure 4. Number of nodes alive over time (a = 5, m = 0.1)

Second, we run simulation for our proposed protocol PBC to compute the round of the first node dies when m=0.2 and a=3. and compare the results of to LEACH, SEP and LEACH-E protocols. Fig. 5 shows the number of round when the first node dies.

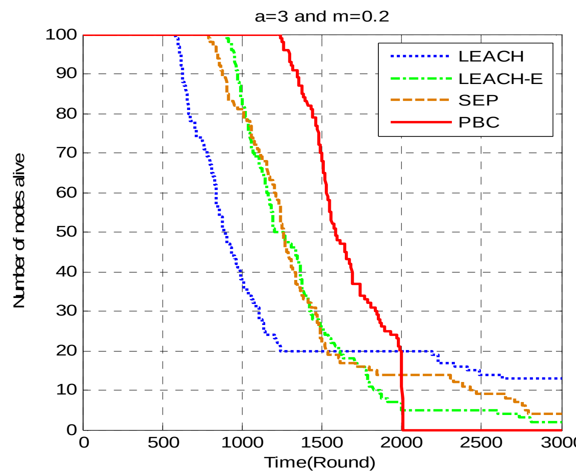

Figure 5. Number of nodes alive over time (a=3, m=0.2).

For SEP, the stability period of SEP is much longer than that of LEACH. Though LEACH-E achieves the stability period longer by about 10% than SEP (see Fig. 5). This is because LEACH-E is an energy-aware protocol, which elects cluster-head according to the residual energy of node. Being also an energy-aware protocol, PBC outperforms other clustering protocols. In fact, PBC obtains 35% more number of round than LEACH-E.

Third, Fig. 6 shows that the number of delivered messages to the BS by PBC protocol are greater than the others ones; this means that PBC is a more efficient protocol.

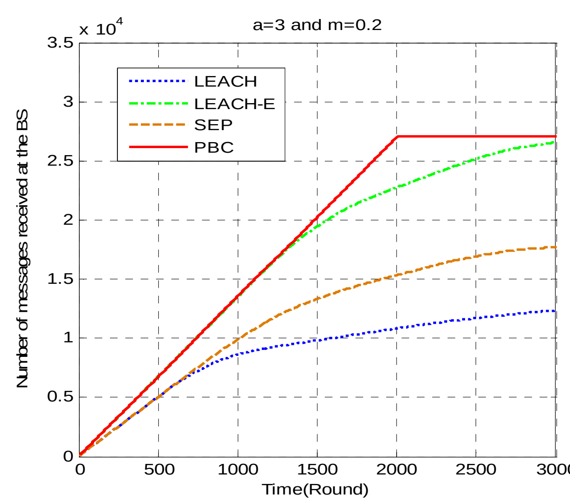

Figure 6. Number of message received at the BS Over time (a = 3, m = 0.2)

Fourth, we run simulation for our proposed protocol PBC to compute the number of received messages at the BS over energy dissipation and compare the results of to LEACH and LEACH-E and SEP protocols. Fig. 7 shows that the messages delivered by PBC to the BS are better than the others ones; this means that PBC is an energy-aware adaptive clustering protocol.

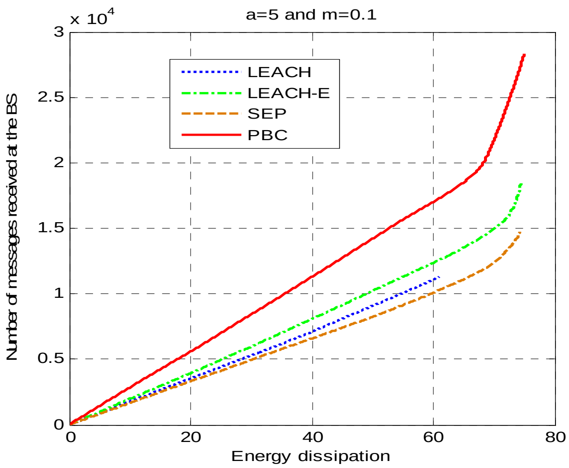

Figure 7. Number of message received at the BS over energy spent (a = 5, m = 0.1).

VI. Conclusion

PBC is proposed as an energy-aware adaptive clustering protocol used in heterogeneous WSNs. To control the energy expenditure of nodes by means of adaptive approach, PBC uses the average energy of the network as the reference energy. Thus, PBC does not require any global knowledge of energy at every election round. Also, by using the position of CHs in cluster formation process, nodes will send their data in effective paths, and do not send their data to the outer place. Moreover, PBC uses the 2-level hierarchy concept which offers a better use and optimization of the energy dissipated in the network. Finally, the introduced modifications enlarge and outperform better the performances of our PBC protocol than the LEACH, LEACH-E and SEP.

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