An Energy Aware, Cluster-based Routing Algorithm for Wireless Sensor Networks⋆

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Abstract. Cluster-based routing protocol has special advantages to enhance scalability and efficiency of the routing protocol. The technique to network clustering that maximizes the network lifetime is an important topic of research in wireless sensor networks. In this paper, we present an energy aware cluster-based routing algorithm (ECRA) for the wireless sensor networks such that the network lifetime can be maximized. ECRA randomly selects some nodes as cluster-heads to construct Voronoi diagram and rotates the intra-cluster nodes to distribute the energy load to all sensors in the network. The simulations show that ECRA algorithm outperforms than direct communication, static clustering and LEACH. The system lifetime of ECRA is approximately 2 times than LEACH. This is because the ECRA rotates intra-cluster-heads to balance the load to all nodes in the sensor networks.

1 Introduction

The technologies of micro-electro-mechanical systems (MEMS) have quickly progressed. These MEMS technologies combine with the wireless communication make it possible to deploy low-cost and low-power sensor network. Many civil and military applications of wireless sensor network such as environmental monitors, informational gathers, battlefields monitors and detecting ambient conditions such as sound, temperature or light. The sensor device has limited energy and transmitting range. Thus, finding the best use for this limited resources is an important and key research topic in wireless sensor network.

Many studies have focused on saving energy in different ways such as reducing the power spent on the modulation circuits[1], or managing the power usage on the MAC layer of sensor nodes [2, 3]. However, these schemes cared of the individual device that is not enough in wireless sensor networks. Since sensor nodes have limited transmitting ranges so that only a few nodes can communicate directly with the sink node. In most cases, the sensor nodes gather sensing data which must be forwarded by other node to the sink node. These relaying operations consume too much energy such that the relay nodes will rapidly expend

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much of their energy. Therefore, developing an energy-aware and load-balanced routing algorithms to maximize the network lifetime has become an important research issue in wireless sensor network.

A large number of routing protocols for wireless sensor networks have been proposed. In the fixed path schemes [4, 5], sensor nodes which are in a fixed path will consume much energy and get exhausted rapidly. This is because they provide relaying service. Flooding scheme consumes too much energy for relaying duplicate packets. Source routing schemes [6, 7] improved the drawback of flooding scheme. However, they can not operate well when the number of hops between source and sink is large. Regarding energy-aware, multi-path routing schemes [8, 9, 10] have the advantage sharing the energy between all sensor in the wireless networks. Nevertheless, the disadvantage of multi-path routing schemes [8, 9] is that the sensor nodes only keep a local view of energy usage and the nodes in the network can not have even traffic dispatch.

There are many studies focus on cluster-based energy-efficient routing protocol for wireless sensor networks [11-19]. The Low Energy Adaptive Clustering Hierarchy (LEACH) [11, 12] randomly selects some nodes as cluster-heads and rotates the cluster-head to distribute the load to all sensors in the wireless sensor networks. It's performance is better than direct communication and static clustering routing protocols. However, the issues of LEACH are as follows: First, if the coverage of cluster-head is too small area, then some cluster-heads will not have any member in its cluster. Second, LEACH has a long latency for the base station to receive the data from the cluster-heads. A chain-based enhanced protocol over LEACH was proposed [13]. It allows nodes need only communicate with their closest neighbors and take turns in communicating with the sink. This routing scheme can increases the operating lifetime of each node and reduces bandwidth consumed. However, this scheme assumes that each node maintains a full database about the position of all other nodes, but the method is not outlined. In [14, 15, 16], a family of adaptive protocols that address the classic flooding using negotiation and resource adaptation was presented. Nevertheless, the high degree nodes of this scheme consume more energy and reduce network lifetime. The above cluster-based schemes require global cluster-heads rotation. This cluster-heads re-election increases many processing and communications overhead. Thus, this paper presents a energy-aware routing scheme to reduce the overhead of cluster-heads rotation for cluster-based wireless sensor networks.

Figure 1 shows an example of wireless sensor network with cluster-based routing scheme. In Figure 1, each cluster has one cluster-head. The non-cluster-head nodes transmit its sensing data to cluster-head which forwards the aggregated data to the sink node. The use of cluster leverages the benefits of small transmit distance for most nodes. The cluster-head acts as a fusion point to aggregate the sensing data such that the amount of data that is actually transmitted to the sink node is reduced [11, 12]. Thus, network clustering can contribute to system lifetime and energy efficiency. Cluster-based routing protocol has special advantages to enhance scalability and efficiency of the routing protocol such as reduces

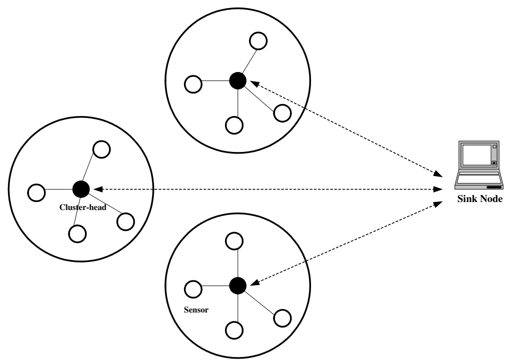

Fig. 1. Wireless sensor network organized in clusters.

the routing complexity [20], reduces the complexity of location management [21], and improves the power control procedure [22]. This technique to network clustering that maximize the network lifetime is an important topic of research in wireless sensor networks. In this paper, we present an energy aware cluster-based routing algorithm (ECRA) for the wireless sensor network such that the network lifetime can be maximized. The ECRA algorithm includes three phases: clustering, data transmission and intra-cluster-head rotation. In our work, we assume that the sensors are location aware. The ECRA algorithm randomly selects some nodes as cluster-heads to construct Voronoi diagram and rotates the intra-cluster nodes to distribute the energy load to all sensors in the network. These are the differences from LEACH. Our motivation is to balance the load to all sensors and avoid too many cluster-heads focusing on the small area. Simulation results show that the system lifetime of ECRA is approximately 2 times than LEACH. ECRA achieves as much as a factor of 9 reduction in the energy dissipation compared with direct communication. This is, ECRA gives better performance than other schemes in system lifetime and energy dissipation. This means that ECRA scheme shares the load evenly to all sensor nodes in the wireless sensor network and it can achieve a better lifetime.

The remainder of this paper is organized as follows. In section 2, we describe energy-based localization. Section 3 illustrates the details of ECRA algorithm. The simulation results and performance analysis are shown in section 4. Finally, the conclusions are given in section 5.

2 The Energy Model of ECRA

In our work, the energy model is the same as in [11]. In this energy model, the electronics energy E_{elec} =50 nJ/bit to operate the transmitter or receiver circuit. The transmitter amplifier $\epsilon_{amp} = 100 \ \ pJ/bit/m^2$. Equations (1) and (2) are used to calculate the transmission energy, denoted as $E_{Tx}(k, d)$, spend for a k bits message over a distance d.

$$E_{Tx}(k,d) = E_{Tx\_elec}(k) + E_{Tx\_amp}(k,d) \quad (1)$$

$$= E_{elec} * k + \epsilon_{amp} * k * d^2 \quad (2)$$

and to receive this message, the energy expends:

$$E_{Rx}(k) = E_{Rx\_elec}(k) = k * E_{elec} \quad (3)$$

Where E_{Tx_elec} is the energy dissipation of transmitter electronics and E_{Rx_elec} is energy dissipation of receiver electronics. E_{Tx_amp} is the energy of transmitter amplifier. Assume that $E_{Tx\_elec} = E_{Rx\_elec} = E_{elec}$. From equation (3), receiving data is also a high overhead procedure. Thus, the number of transmission and receiving operations must be minimized to reduce the energy dissipation. We also assume that the radio channel is symmetric such that the energy required to transmit a message from node i to node j is the same as the energy required to transmit a message from node j to node i for a given signal to noise ratio.

3 The Details of ECRA

The ECRA algorithm includes the following three phases: clustering, data transmission and intra-cluster-head rotation. The details of the algorithm are given as follows.

Phase 1: Clustering

Initially, the base station randomly selects 5 percentage[1] of total sensor nodes as the cluster heads and informs these nodes that they will become cluster-heads. The set of cluster-heads is denoted as S_c. CH_i represents the cluster-head of cluster i. The set of nodes is denoted as S_n. N_{ij} represents node j of cluster i (It is shown in Figure 2). In this wireless sensor networks, the locations of the sensors are static such that the intersection area can be determined by Voronoi diagram.

We define the Voronoi diagram as follows [23, 24]. Assume that $P = \{p_1, p_2, ..., p_n\}$ stands for the set of points in the n-dimensional space. Their location vectors of p_i and p_j is denoted as l_i and l_j. $l_i \neq l_j$, $\forall i \neq j$. The region that is given by $S(p_i) = \{l \mid \parallel l - l_i \parallel \leq \parallel l - l_j \parallel, \forall i \neq j\}$ that is called the Voronoi region.

[1] This parameter has minimal normalized total energy dissipation [11].

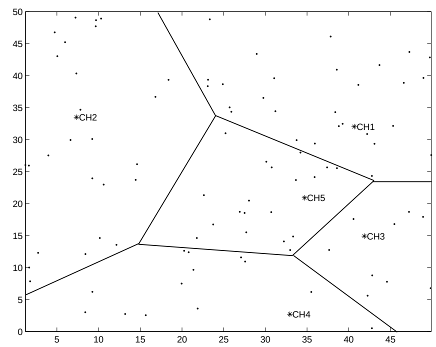

Fig. 2. Voronoi diagram of the 100-node random sensor network.

$V(P) = \bigcup_{1 \leq i \leq N} S(p_i)$ is called the Voronoi diagram. The half-space is bounded by the hyperplane that is perpendicular bisector of a segment. $S(p_i)$ is the intersection area of these half-space. Therefore, the Voronoi region can defined as follow. $S(p_i) = \bigcap_{1 \leq j \leq N, j \neq i} h(p_i, p_j)$. Where, $h(p_i, p_j)$ stands for the half-space containing p_i. In our ECRA scheme, the Voronoi diagram is applied for network clustering. The base station constructs Voronoi diagram to cover the sensing field and selects a sensor node as cluster-head for each Voronoi cell. The base station also informs each cluster-head which nodes are its members. The cluster-head broadcasts an advertisement message to their members. After each node known which cluster it belongs, then it informs the cluster-head that it will be a member of the cluster using a CSMA MAC protocol. During this time, all cluster-heads must keep in active.

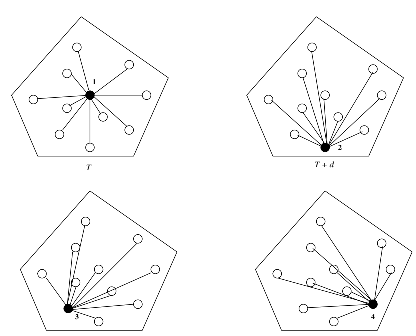

Fig. 3. An example of intra-cluster-head rotation. Where T is the current round and $T + d$ is the next round, and so on.

Phase 2: Data transmission

When the clusters are created such that the data transmission can begin. The nodes use single hop to communicate with their cluster-heads, and the cluster-heads also use single hop to communicate with the base station. Each node has M bits messages to transmit. The non-cluster-head node can turned-off until its allocated transmission time to minimize the energy dissipation. When all data from the nodes has been received, the cluster-head aggregates the total data into a single message to reduce the amount of information that transmitted to the base station.

Phase 3: Intra-cluster-head rotation

When a round is end, then rotate the cluster-head within the same cluster based on a parameter called O_{ij} which considers the distance from node j in cluster i to base station and the residual energy of each node. The distance from node j in cluster i to base station is denoted as d_{ij}.

$$d_{ij} = \sqrt{(X_{ij} - X_{bs})^2 + (Y_{ij} - Y_{bs})^2} \tag{4}$$

$$E_{new} = E_{old} - E_{expend} \tag{5}$$

$$O_{ij} = \frac{E_{new}}{d_{ij}} \tag{6}$$

Where the position of node j in cluster i is at (X_{ij}, Y_{ij}) and the position of base station is at (X_{bs}, Y_{bs}). In equation (5), E_{old} is the residual energy of each node at current round and E_{new} is the residual energy of each node at next round. E_{expend} is the energy expend of each node in the current round. From equation (6), O_{ij} is a function of d_{ij} and E_{new}. The node with the maximal value of O_{ij} will become a cluster-head at the next round (It is shown in Figure 3). When all data are received in current round. The base station informs the cluster-head of current round that the other node will become the new cluster-head $CH_{i,new}$ at next round. The base station has the location of each node and it can calculate the value of O_{ij}. When the current round is end, the cluster-head will rotate to the other node that informed by the base station. Then, the new cluster-head begins to advertise using the same method as phase 1. The pseudo code of ECRA algorithm is shown in Table 1.

4 Simulation Results

4.1 Performance Metrics and Environment Setup

This section presents the performance analysis of the ECRA algorithm. The metrics for performance are given as follows.

1) The lifetime for first node to die (FND): FND is defined as the time that

Table 1. The pseudo code of ECRA algorithm

```
begin Clustering
  Randomly select cluster-heads
    for (every S_c)
      Construct Voronio diagram
    end for
end Clustering
begin Data transmission
while ( data size < M )
      for ( every S_c )
         for ( every N_ij )
            Transmit data
         end for
      end for
end while
end Data transmission
begin Intra-cluster-head rotation
while ( data size = M )
      for ( every S_c )
         for ( every N_ij )
            Calculate O_ij
            CH_{i,new} = N_ij
            j = j + 1
         end for
      end for
end while
end Intra-cluster-head rotation
```

the first node run out of energy. The non-cluster-head nodes transmit their sensing data to cluster-head. The cluster-heads returned their aggregated data to the sink periodically. We use the number of *rounds* to represent the network lifetime of FND. A round is defined as all nodes in the wireless network that finish returning their gathered data to the sink. The time interval between two rounds is assumed to be large enough for last node to return its sensing data.
2) The lifetime for last node to die (LND): LND is defined as the time that last node run out of energy and the network crashed. We also use the number of *rounds* to represent the network lifetime of LND.
3) The total energy dissipation: This value is defined as the energy dissipation for all nodes that finish returning their gathered data.

Four different sizes of deploying regions were simulated. There are $50\times50\ \ m^2$, $100\times100\ \ m^2$, $150\times150\ \ m^2$ and $200\times200\ \ m^2$. In each region, 100 nodes was deployed by uniform distribution. Assume that the energy model is the same as in [11]. The electronics energy E_{elec} =50 nJ/bit. $\epsilon_{amp} = 100\ \ pJ/bit/m^2$. The energy of data aggregation is 5 nJ/bit/message. There is a 100 - node random network with 5 percentage cluster heads. The sink node was located at the position (x = 25, y = -100). Each sensor has 2000 bits data packet to the base station during each round. We evaluate three performance metrics of ECRA and compare with other schemes.

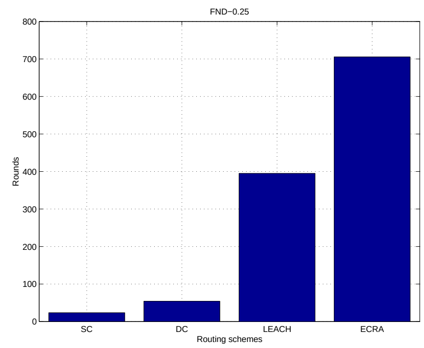

Fig. 4. The lifetime of first node died (FND) under different methods. The initial energy of each sensor is 0.25

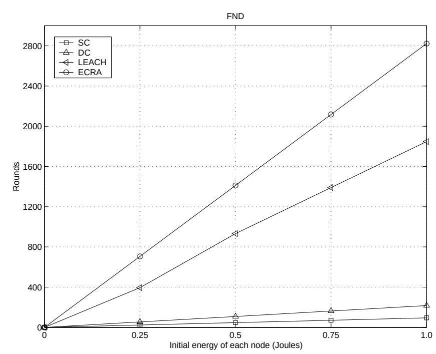

Fig. 5. The lifetime of first node died (FND) using different amounts of initial energy for the sensors.

4.2 Numerical Results

Comparisons of the three performance metrics were made for four schemes: the direct communication (DC), static clustering (SC), LEACH and ECRA. These performance metrics includes the FND, LND and total energy dissipation in the system that will illustrate as follows.

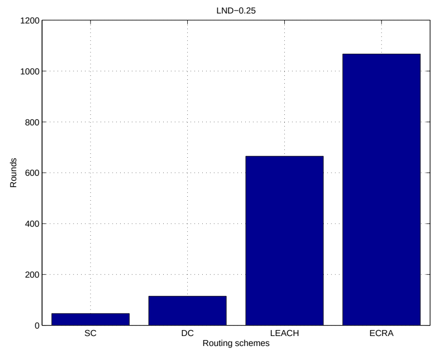

Fig. 6. The lifetime of last node died (LND) under different methods. The initial energy of each sensor is 0.25

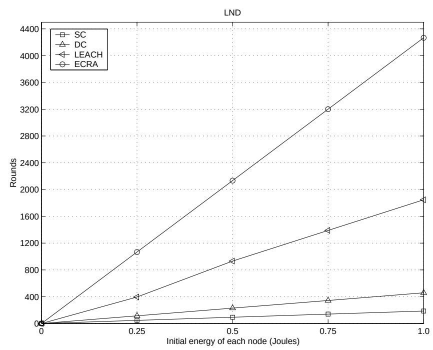

Fig. 7. The lifetime of last node died (LND) using different amounts of initial energy for the sensors.

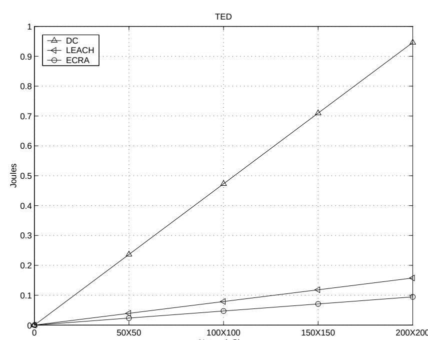

Fig. 8. Total energy dissipation (TED) using direct communication, LEACH and ECRA. The messages are 2000 bits.

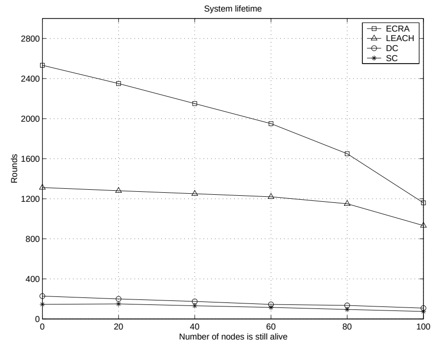

Fig. 9. System lifetime using direct communication, static clustering, LEACH and ECRA with 0.5 J / node.

1) The lifetime of FND under different initial energy

Figure 4 shows that the lifetime of ECRA in FND is approximately 1.8 times than LEACH, 13 times than direct communication and 29 times than static clustering if the initial energy of each sensor is 0.25 J. Figure 5 shows that the lifetime of FND under different methods with different initial energy of each node. Overall, the lifetime of FND is increasing when the initial energy of each sensor is greater. This figure shows that the lifetime of FND in ECRA is approximately up to 2 times than LEACH, over 13 times than direct communication and static clustering. That is, ECRA gives better performance than DC, SC, and LEACH in the lifetime of FND.

2) The lifetime of LND under different initial energy

Figure 6 shows that the lifetime of ECRA in LND is approximately 1.7 times than LEACH, 10 times than direct communication and 23 times than static clustering if the initial energy of each sensor is 0.25 J. Figure 7 shows that the lifetime of LND under different methods with different initial energy of each node. Overall, the lifetime of LND is increasing when the initial energy of each sensor becomes large. This figure shows that the lifetime of LND in ECRA is approximately up to 2 times than LEACH, over 18 times than direct communication and static clustering. The results show, ECRA gives better performance than DC, SC, and LEACH in the lifetime of LND. From Figure 5 and Figure 7, note that a scheme shares the load evenly to all sensor nodes in the network, it can achieve a better lifetime.

3) Total energy dissipation under different network diameter

Figure 8 shows that ECRA achieves as much as a factor of 9 reduction in the energy dissipation compared with direct communication. This means that the use of cluster leverages the benefits of small transmit distance for most nodes and distributes the energy among the sensor nodes in the network can reduce total energy dissipation.

Figure 9 shows that the system lifetime is decreasing when the the number of rounds is greater. From this figure shows that the system lifetime of ECRA is approximately 2 times than LEACH. According to above analysis, our ECRA algorithm has better performance than other schemes in system lifetime and energy dissipation. These simulation results show that ECRA has the advantages of load-balancing and energy-saving.

5 Conclusions

Cluster-based routing protocol has special advantages to enhance scalability and efficiency of the routing protocol. This paper presents an energy aware cluster-based routing algorithm for wireless sensor networks. Compared with direct communication, static clustering and LEACH, our ECRA scheme can achieve longer lifetime. This is because the ECRA rotates intra-cluster-heads to balance the load to all nodes in the sensor networks. The numerical results show that ECRA gives better performance in load-balancing and energy-saving than other schemes. We are confident that ECRA is an efficient and useful algorithm for further wireless ad hoc sensor networks.

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