IDUC: An Improved Distributed Unequal Clustering Protocol for Wireless Sensor Networks*

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Abstract. Due to the imbalanced energy consumption among nodes in wireless sensor networks, some nodes die prematurely, which decreases the network lifetime. To solve this problem, existing clustering protocols usually construct unequal clusters by exploiting uneven competition radius. Taking their imperfection on designing the uneven competition radius and inter-cluster communication into consideration, this paper proposes an improved distributed unequal clustering protocol (IDUC) for wireless sensor networks, where nodes are energy heterogeneous and scattered unevenly. The cores of IDUC are the formation of unequal cluster topology and the construction of inter-cluster communication routing tree. Compared with previous protocols, IDUC is suitable for various network scenarios, and it can balance the energy consumption more efficiently, and extend the lifetime of networks significantly.

1 Introduction

A wireless sensor network (WSN) consists of plentiful low-power sensor nodes capable of sensing, processing and communicating. These sensor nodes observe the environment phenomenon at different points in the field, collaborate with each other and send the monitored data to the Base Station (BS). As sensor networks have limited and non-rechargeable energy resources, energy efficiency is a very important issue in designing the network topology, which affects the lifetime of WSNs greatly. Thus, how to minimize energy consumption and maximize network lifetime are the central concerns when designing protocols for WSNs.

In recent years, clustering has been proved to be an important way to decrease the energy consumption and extend lifetime of WSNs. In clustering scheme, sensor nodes are grouped into clusters, in each cluster, a node is selected as the

* The work is supported by NNSF of China for contract(61373027, 11101243) and NSF of Shandong Province for contract(ZR2012FM023).
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Z. Cai et al. (Eds.): WASA 2014, LNCS 8491, pp. 682–693, 2014.

leader named as the cluster head (CH) and the other nodes are called cluster members (CMs). Each CM measures physical variables related to its environment and then sends them to their CHs. When the data from all CMs is arrived, CHs aggregate data and send it to the BS. Since CHs are responsible for receiving and aggregating data from their CMs, and then transmitting the aggregated data to the specified destination, the energy consumption of which is much higher than that of CMs. To solve this problem, most clustering algorithms divide the operation into rounds and periodically rotate the roles of CHs in the network to balance the unequal energy consumption among nodes. However, there exists another problem, that is, energy consumption among CHs is also imbalanced due to the distance to the BS. In single-hop networks, CHs farther away from the BS need to transmit data to a long distance. Thus, the energy consumption of these CHs is larger than that of CHs closer to the BS. In multi-hop networks, CHs closer to the BS undertake the task of forwarding data, which means that the energy consumption of CHs closer to the BS is larger. The imbalanced energy consumption of nodes leads to a certain number of nodes dying prematurely, causing network partitions. To solve this problem, researchers design unequal clustering algorithms to balance the energy consumption among CHs.

In this paper, aiming at energy heterogeneous networks where nodes are deployed unevenly, a more practical network case, we propose an improved distributed unequal clustering protocol (IDUC), in which a new competition radius and a new inter-cluster communication routing tree are designed to balance the energy consumption among CHs and extend the network lifetime.

The rest of the paper is organized as follows. Section 2 introduces the related works in this field. Section 3 gives the network model and related problem description. Section 4 presents the improved distributed unequal clustering protocol in details. Section 5 analyzes several properties of our algorithm. In Section 6,concludes the paper.In Appendix,exhibit and analyze simulation results.

2 Related Works

Since the energy consumption of CHs is much larger than that of CMs, in order to balance the energy among nodes, most clustering protocols adopt a rotation mechanism of CHs. The rotation methods used by the existing clustering algorithms can be divided into time-driven rotation and energy-driven rotation. In time-driven clustering algorithms [1-5], the role of the CH is rotated in the entire network periodically according to a predetermined time threshold. As each rotation is carried out in the entire network, the large overhead of re-cluster causes a lot of unnecessary energy waste. In energy-driven clustering algorithms [6-11], the role of CH is rotated when the residual energy of CH is less than a threshold. Re-cluster process only happens in local area, thus the large cost of global topology reconstruction can be avoided.

However, aside from the imbalance energy consumption among CHs and CMs, there also exists another imbalance consumption phenomenon among CHs that can impact the network lifetime significantly. To solve this problem, many unequal clustering algorithms have been proposed. The unequal clustering algorithms proposed in [12-14] all divide the network field into cirques. In [12], clusters in the same cirque have the same size, whereas clusters in different cirques have different sizes. Some high-energy nodes are deployed to take on the CH role to control network operation, which ensures that the energy dissipation of nodes is balanced. In [13], a cirque-based static clustering algorithm for multi-hop WSNs is proposed. Clusters closer to the BS have smaller sizes. Utilizing virtual points in a corona-based WSN, static clusters with dynamic structures are formed in ERP-SCDS [14].

The communication way of CHs in the distributed clustering protocol EECS [15] is single-hop, and the protocol adopts a weighted faction to control the numbers of CMs to construct unequal clusters. That is, the cluster size is smaller if it is farther away from the BS, vice versa.

EEUC [16] is also a distributed unequal clustering algorithm with inter-cluster multi-hop communication, which elects CHs based on the residual energy of nodes. Each node becomes a tentative CH with a probability T. However, the competition radius used by EEUC is not ideal for heterogeneous WSNs, and since the quality of the generated CHs is affected by T, there also exists "isolate points" in EEUC in some cases. LUCA [17] is similar to EEUC but presents more accurate theoretical analysis of optimal cluster size based on the distance between the CH and the BS.

In [18], we proposed EADUC to overcome the defects of EEUC. When designing the competition radius, besides the distance between nodes and the BS, the residual energy of nodes is also taken into account. That is, CHs closer to the BS and possessing lower residual energy have smaller cluster sizes to preserve some energy for the inter-cluster data forwarding, thus the cluster size is more reasonable and more suitable for heterogeneous WSNs. Simultaneously, EADUC overcomes the "isolate points" problem.

These protocols described above, such as EEUC, only considers the distance between nodes and the BS, which is not suitable for heterogeneous networks, thus EADUC also takes residual energy of nodes into account besides the distance factor. However, they all overlook the distribution of nodes in WSNs, it is not always effective to apply these algorithms into networks where nodes are scattered unevenly.

Aiming at this problem, what we need to do is to design a protocol, which is suitable for various network scenarios, an improved distributed unequal clustering protocol (IDUC) is proposed in this paper. IDUC is effective in both heterogeneous and homogeneous network scenarios, simultaneously, it is suitable for WSNs where nodes are scattered evenly or unevenly. Our main contribution in the paper is as follows: 1) a new cluster head competition radius is proposed, it considered the distance among nodes and the BS, the residual energy of nodes and the number of neighbor nodes within the nodes' communication range.

2) To meet the gap between the number of nodes within the communication ranges and the finally cluster ranges, when designing the inter-cluster routing tree, CHs will choose CH nodes that possessing higher energy and fewer CMs as their next hops.

3 Network Model and Problem Description

A. Network Model

To simplify the network model, we adopt a few reasonable assumptions as follows.

1. There are N sensor nodes that are distributed in an $M \times M$ square field.
2. The BS and all nodes are stationary after deployment.
3. All nodes can be heterogeneous.
4. All nodes are location-unaware.
5. All nodes can use power control to adjust the transmit power.
6. The BS is out of the sensor field. It has enough energy, and its location is known by each node.
7. Each node has a unique identity *id*.

To transmit an l-bit data to a distance d, the radio expends energy is

$$E_{T_x}(l,d) = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d^2, & d < d_0 \\ l \times E_{elec} + l \times \varepsilon_{mp} \times d^4, & d \geq d_0 \end{cases} \tag{1}$$

Where d is the transmission distance,E_{elec}, ε_{fs} and $\varepsilon_{mp}$are parameters of the transmission/reception circuit. According to the distance between the transmitter and receiver, free space ε_{fs}or multi-path fading ε_{mp} channel models is used. While receiving an $l - bit$ data, the radio expends energy is

$$E_{Rx}(l) = l * E_{elec}. \tag{2}$$

B. Problem Description

As described above, some clustering protocols construct unequal clustering topology by uneven cluster head competition radius. However, these protocols, such as EEUC, only considers the distance between nodes and the BS, which is not suitable for heterogeneous networks, thus EADUC also takes residual energy of nodes into account besides the distance factor. Nonetheless, if we applied these algorithms into networks where nodes are scattered unevenly, such case is very likely to appear as shown in Figure 1, if the distance between s_i and BS is near to the distance between s_j and BS, meanwhile, the residual energy of s_i and s_j is also approximate, it is notable that the number of CMs within the cluster range of s_i is much larger than s_j , which can also lead to the imbalanced consumption of s_i and s_j.

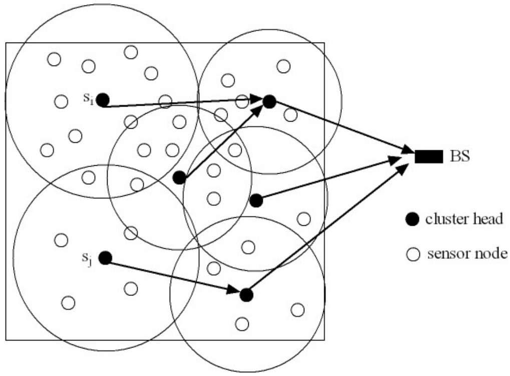

Fig.1. Imbalance energy consumption between s_i and s_j

Meanwhile, in most practical applications, the deployment of nodes in networks is not always uniform. If nodes are unevenly scattered, the nodes density is different in different area of the network. In such scenario, case appearing in Figure 1 easily happen when we applied exist clustering protocol. Thus, we need to control the number of CMs of each cluster, that is, if nodes have more communication neighbor nodes, their cluster competition radius should be smaller, vice versa. In fact, it is easy to obtain a method to solve this problem, as shown in Figure 1that is to reduce the competition radius of s_i, and to increase the competition radius of s_j, correspondingly. With the adjustment of competition ranges, the numbers of CMs covered by s_i and s_j are all adjusted to be more reasonable. Thus, it is necessary to design a new CH competition radius for such networks, besides the distance from the nodes to BS and the residual energy of nodes, we also take the number of neighbor nodes within the nodes' communication range into account.

However, we have to admit that the number of neighbor nodes within the node initial communication range is very likely to be not equal with the number of CMs within its finally cluster range. Thus, to further balance the consumption among CHs, when we construct the inter-cluster multi-hop routing tree, each CH needs to count the number of its CMs, and then it chooses the neighbor CH with fewer CMs and higher residual energy as its next hop.

4 IDUC Details

The whole operation is divided into rounds, where each round contents a cluster set-up phase and a data transmission phase. In the cluster set-up phase, a clustering topology is formed, and in the data transmission phase, a new routing tree is constructed to forward data. To save energy, the data transmission phase should be longer than the cluster set-up phase. The description of node states and several control messages are shown in Table 1, respectively.

Table 1. Description of control messages

Message	Description
Node_Msg	Tuple(selfid,selfenergy)
Head_Msg	Tuple(selfid)
Join_Msg	Tuple(selfid,headid)
Schedule_Msg	Tuple(schedule,order)
Route_Msg	Tuple(selfid,selfenergy)

A. Cluster Set-up Phase

In the network deployment phase, the BS broadcasts a signal, each node can compute its approximate distance to the BS based on the received signal strength, this step is necessary when designing an unequal distributed clustering algorithm. The following is the cluster set-up phase. The first sub-phase of this phase is information collection phase, whose duration is set as T_1. At the beginning of this phase, each node broadcasts a *Node_Msg* message within its communication range r, the message contains the node id and its residual energy. Meanwhile, the node will receive *Node_Msgs* from its neighbor nodes, and each node calculates the average residual energy E_{ia} of its neighbor nodes by using the following formula.

$$E_{ia} = \frac{1}{n} * \sum_{j=1}^{n} E_{jr}. \tag{3}$$

Where n denotes the number of neighbor nodes of s_i, E_{jr} denotes the residual energy of the jth neighbor of s_i. For any node s_i, it calculates its waiting time ti for broadcasting the *Head_Msg* message according to the following formula.

$$t_i = \begin{cases} \frac{E_{ia}}{E_{ir}} T_2 V_r, & E_{ir} \geq E_{ia} \\ T_2 V_r, & E_{ir} < E_{ia} \end{cases} \tag{4}$$

Where V_r is a real value randomly distributed in [0.9, 1], which is introduced to reduce the probability that two nodes send *Head_Msgs* at the same time. After T_1 expires, it starts the next sub-phase, cluster head competition phase, whose duration is set as T_2. In this phase, for any node s_i, if it receives no *Head_Msg* when time ti expires, it broadcasts the *Head_Msg* within competition range R_c to advertise that it will be a CH. Otherwise, it gives up the competition. In order to generate unequal clusters, these nodes need to calculate their own competition radius R_c. In [15], based on the distance between nodes and BS, the formula of R_c is as follows.

$$R_C = [1 - \alpha \frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}}] R_{max}. \tag{5}$$

Where d_{max} and d_{min} are the maximum and minimum distance from nodes to the BS, $d(s_i, BS)$ is the distance from node s_i to the BS, α is a weighted factor whose value is in [0, 1], and R_{max} is the maximum value of competition radius. By analyzing the formula (5), we can obtain that a larger $d(s_i, BS)$ can generates a larger R_C, which can guarantee that CHs farther away from the BS will control larger cluster areas, whereas CHs closer to the BS can control smaller cluster areas.

In heterogeneous networks, nodes have heterogeneous initial energy. In the case that each node has the same energy consumption, nodes with low initial energy will die prematurely, reducing the network lifetime. In order to take full advantage of high-energy nodes, these high-energy nodes should take more tasks. Therefore, considering both the distance from nodes to the BS and the residual energy of nodes, we gave an improved formula of R_C in EADUC [18] as follows.

$$R_C = [1 - \alpha\frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}} - \beta(1 - \frac{E_{ir}}{E_{max}})]R_{max}. \quad (6)$$

Where α and β is the weighted factors in [0, 1], E_{ir} is the residual energy of node s_i. From the above formula we can see that the competition radius of the node is determined by $d(s_i, BS)$ and E_{ir}. Formula (6) means that CHs with higher residual energy and farther away from the BS will control larger cluster area.

However, the cluster competition radius R_c designed above are all not suitable for networks where nodes are scattered unevenly, especially when the distance between these nodes and BS is similar, and the residual energy of these nodes is also approximate. Thus, we need to design a new competition radius to avoid imbalanced energy consumption in such case.

Meanwhile, another remarkable problem generated in EADUC is that there is not a restriction on the relation of α and β, thus in such case where both $\frac{d_{max}-d(s_i,BS)}{d_{max}-d_{min}}$ and $1-\frac{E_{ir}}{E_{max}}$ are large, and their weighted factor and are also large, then the R_c we obtain is likely to be a negative value, which is not meaningful in practical applications, therefore, it is necessary to give a limit on the relation of α and β. Aiming at above disadvantages of existing R_c, we propose a new cluster head competition radius R_c, which is set as follows.

$$R_C = [1 - \alpha\frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}} - \beta(1 - \frac{E_{ir}}{E_{max}}) - \gamma(\frac{n_i}{N - n_i})]R_{max}. \quad (7)$$

Where N denotes the number of nodes in the network, n_i is the number of neighor nodes within the communication range of s_i. α , β and γ is the weighted factors in [0,1] , and we set $\alpha + \beta + \gamma \leq 1$. Formula (7) means that CHs closer to the BS, with lower residual energy and more communication neighbor nodes will have smaller cluster size. In conclusion, firstly, CHs closer to the BS can save energy for data forwarding. Secondly, CHs with lower residual energy dominating smaller clusters can avoid their premature death and prolong the network lifetime. Thirdly, CHs with more communication neighbor nodes control smaller clusters, which makes the competition radius more suitable for nonuniform networks. Obviously, R_c in formula (7) makes IDUC suitable for various network scenarios:

(1) If the network is energy homogeneous, we can set $\beta = 0$ and $\alpha + \gamma \leq 1$.

(2) If the distribution of nodes in the network is uniform, we can set $\gamma = 0$ and $\alpha + \beta \leq 1$.

(3) If nodes in the network is energy homogeneous and the distribution is nonuniform, we can set $\alpha + \beta + \gamma \leq 1$.

According to practical network applications, we can adjust α , β and γ , and to be the optimal value to extend the network lifetime.

When T_2 expires, the next sub-phase is the cluster formation phase, whose duration is T_3. In this phase, each plain node chooses the nearest CH and sends the *Join_Msg*, which contains the id and its residual energy. According to the received *Join_Msgs*, each CH creates a node schedule list including the *Schedule_Msg* for its CMs. At this point, the entire cluster set-up phase is completed. The following pseudo-codes give the details of the whole cluster set-up phase.

```
begin (cluster set-up algorithm)
    state ← Plain
    Broadcast the Node_Msg
    while (T1 has not expired)
        Receive Node_Msgs
        Update neighborhood table NT[ ]
    end while
    ti ← broadcast waiting time for competing a CH
    while (T2 has not expired)
        if CurrentTime < ti
            if receive a Head_Msg from a neighbor NT[i]
                state ← Plain
                NT[i].state ← CH
            else
                Continue
            end if
        else if state = Plain
            state ← CH
            Rc ← competing radius
            Broadcast the Head_Msg
        end if
    end while
    while (T3 has not expired)
        if state = Plain&& has not sent Join_Msg
            Send Join_Msg to the nearest CH
        else
            Receive Join_Msg from its neighbor nodes
        end if
    end while
    if state = CH
        Broadcast the Schedule_Msg
    end if
end
```

B. Data Transmission Phase

In the data transmission phase, each CM collects local data from the environment periodically and then sends the data to the CH within its time slot according to the TDMA scheduling list to avoid the collisions among the members in the same cluster. When data from all the member nodes has arrived, the CH aggregates the data and sends it to the BS. Thus, this section is divided into two sub-phases, $intra-clustercommunication$ and $inter-clustercommunication$. CMs sense and collect local data from the environment, and send the collected data to CHs. This process is called intra-cluster communication. For simplification, CMs communicate with CHs directly, just like LEACH.

In inter-cluster communication phase, we will construct a routing tree on the elected CH set, each CH will forward these data they have collected and aggregated from their CMs to the BS by other CHs. This multi-hop communication from CHs to the BS will further reduce and balance the energy consumption.

Several nodes need to be selected as child nodes of the BS from all CHs, and communicate with the BS directly. Therefore, each CH determines whether to be selected as the child node of the BS depending on its distance to the BS according to a threshold Euclidean distance $DIST$. If the distance from CH s_i to the BS is less than $DIST$, s_i communicates with the BS directly, and sets the BS as its next hop. Otherwise, it communicates with the BS through a multi-hop routing tree.

The concrete process is as follows. We set the duration as T_4. At the beginning, each CH broadcasts a $Route\_Msg$ message within the radio radius R_r with the values of the id, the residual energy and the distance to the BS. To ensure the connectivity of all CHs, we set the radio radius $R_r = 3R_c$. If the distance from CH s_i to the BS is less than $DIST$, it chooses the BS as its next hop. Otherwise, it chooses its next hop according to these received $Route\_Msgs$. CH s_i chooses the neighbor CH with higher residual energy, fewer CMs and no farther away from the BS as its next hop. We give the formula of "Cost" when CH s_i chooses CH s_j as its next hop as follows

$$Cost(s_i, s_j) = \omega \frac{E_{jr}}{E_{max}} + (1 - \omega)(1 - \frac{n_j}{N}) \quad (8)$$

Where E_{jr} denotes the residual energy of CH s_j, n_j denotes the number of CMs of s_j. ω is a random value in [0,1], and it is used to determine which factor is more important in choosing the next routing node. We can obtain from (8) that, nodes with higher residual energy and fewer CMs have larger cost value.

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begin (cluster-based routing algorithm)
  Broadcast the $Router\_Msg$
  if ($disttoBS < DIST$)
    $nexthop \leftarrow BS$
  else
    while(T has not expired)
      Receive Router_Msgs

```
            Compute the cost
            Update CH neighborhood table CHNT[]
        end while
    end if
    if s_j has the max value of cost in CHNT[]
      &&s_j has a smaller disttoBS in CHNT[]
      Update MR[]
    end if
    end
```

5 Protocol Analysis

Theorem 1. *There is at most one CH within each cluster competition radius* R_c*.*

Proof. As we state previously, formula (4) ensures that different nodes have different waiting time. Assume that node s_i has a shorter waiting timer than others and broadcasts the $Head\_Msg$ within radius R_c. Thus, all nodes within this range will give up the competition and become plain nodes. Therefore, there is no more than one CH within the radius R_c of any CH.

Theorem 2. *The cluster head set generated by the IDUC algorithm is a dominating set.*

Proof. According to theorem 1, there is no more than one CH within a cluster, so the cluster head set must be an independent set. After the execution of the IDUC algorithm, each node in the network either is the CH, or the member node of one cluster, any plain node adding to the cluster head set will destroy its independence, Hence, he cluster head set is the maximum independent set. Since the maximum independent set is also a dominating set, the cluster head set generated by the IDUC algorithm is a dominating set.

Theorem 3. *The cluster head set generated by IDUC can cover all the network nodes.*

Proof. (a) When $E_{ir} \geq E_{ia}$, we have $t_i = \frac{E_{ia}}{E_{ir}} T_2 V_r$ according to formular(4). Thus, we can obtain $t_i \leq T_2$ since $V_r \leq 1$. (b) When $E_{ir} \leq E_{ia}$, we have $t_i = T_2 V_r$ according to formula(4). Thus $t_i \leq T_2$, since $V_r \leq 1$.

Therefore, we conclude that the waiting time of any node is smaller than T_2. That is, any expected CH will broadcast a $Head\_Msg$ and become a CH before T_2 expired, which can avoid the generation of "isolate points".

Theorem 4. *The overhead complexity of control message in the network is* $O(N)$ *and the time complexity of IDUC is* $O(1)$*.*

Proof. At the beginning of each round, each node broadcasts a $Node\_Msg$. Thus, there are N $Node\_Msgs$ in the whole network. In each round, each CM broadcasts a $Join\_Msg$, while each CH broadcasts a $Head\_Msg$, a $Schedule\_Msg$ and a $Route\_Msg$. Suppose the number of generated CHs is k, then the total number of $Join\_Msgs$ is $N - k$, and the numbers of $Head\_Msgs$, $Schedule\_Msgs$ and $Route\_Msgs$ messages are all k. Thus, the total number of control messages in the entire network is $N+(N-k)+k+k+k = 2N+2k$. Therefore, the overhead complexity of control messages in the network is $O(N)$.

6 Conclusion

In this paper, an improved distributed unequal clustering protocol is proposed, we design a new cluster competition radius considering the distance between nodes and the BS, the residual energy of nodes and the numbers of neighbor nodes within the node communication range. Furthermore, to bridge the gap between the numbers of nodes within the initial communication radius and the finally cluster radius, we design a new inter-cluster communication routing tree. Theoretical analysis and simulation show that, the protocol is suitable for various network scenarios, In these scenarios, the nodes energy can be efficiently balanced and the network lifetime can be extended significantly.

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