A Cluster Head Election Method with Adaptive Separation Distance and Load Distribution for Wireless Sensor Networks

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***Abstract*— Cluster based wireless sensor networks have the advantage of reduced energy consumption and increased message delivery compared to the situations where no hierarchical communication is used. Cluster heads (CHs) play the important role of performing data gathering and aggregation from surrounding nodes and thus must be efficiently chosen. This paper describes a CH election algorithm for wireless sensor networks (WSNs) based on LEACH that uses adaptive separation distance and load distribution (LEACH-ASDLD) in order to enhance network lifetime and message delivery. The proposed algorithm considers the number of neighbors in the vicinity of each node as well as the expected packet size to be transmitted in electing the appropriate CH, thus distributing network load among key sensors within the network rather than evenly distributing the load among all nodes. Using adaptive separation distance determines the number of CHs per round and ensures their uniform spread over the observation area. In order to determine the importance of using adaptive separation distance combined with load distribution we have performed Matlab simulations and compared our algorithm with a minimum separation distance (MSD) algorithm entitled Improved Minimum Separation Distance (IMSD), an enhancement to MSD. Our simulations show that using the proposed algorithm can extend the lifetime of the network and provide increased message delivery by up to 15% depending on the simulated network and packet sizes.**

Keywords-clustering, adaptive separation distance, load distribution, wireless sensor networks

I. Introduction

Wireless sensor networks are intelligent networks comprised of hundreds, even thousands of nodes that collaborate to perform various sensing tasks. Their unique characteristics such as low cost, reduced size, low power consumption and rapid deployment make WSNs the best solution for numerous applications such as military surveillance, detection of chemical activity, environmental and healthcare monitoring, to mention just a few. Deploying such networks in dangerous and inaccessible environments allows for the extraction of information which would otherwise be very difficult if not impossible to obtain. However, due to the fact that sensor nodes are battery powered energy consumption at the node and network level is of high importance and represents a major challenge in the design of WSNs. Network lifetime is defined as the time elapsed until the first, half, or the last node in the network consumes its energy. To address the issue of energy efficiency at the network level, intelligent routing protocols are adopted which currently fall under two categories: flat routing protocols and hierarchical routing protocols.

Flat routing protocols consider all nodes within the network as equal and routes are generated through feedback information instead of using a hierarchical management mechanism. The main advantage of this technique is that network traffic is evenly distributed among network nodes [1]. Flat routing protocols include techniques like gossiping and flooding [2], spin [3] and directed diffusion [4].

Hierarchical routing protocols divide the observation area (OA) into smaller areas named clusters and assign representative nodes entitled cluster heads (CHs) that manage the communication within nodes in the cluster and transmit the obtained data to the base station (BS) or to other CHs along the path to the BS. The way clusters are defined, how the CHs are elected and how the communication with the BS is performed, depends on the elected routing protocol. Several representative hierarchical routing protocols for WSNs are LEACH (Low-Energy Adaptive Clustering Hierarchy) [5], TEEN (Threshold sensitive Energy Efficient sensor Network protocol) [6], PEGASIS (Power-Efficient GAthering in Sensor Information Systems) [7] and others more recent that are mostly improvements to the previously mentioned ones.

The rest of this paper is structured as follows: Section II provides a description of the LEACH [5], MSD [8] and IMSD [9] protocols and Section III describes the proposed algorithm LEACH-ASDLD. Section IV describes the experimental setup, as well as the obtained results and Section V presents conclusions and future work.

II. Related work

A. The LEACH protocol

The Low-Energy Adaptive Clustering Hierarchy (LEACH) [5] is a cluster based protocol that reduces the energy consumption of the sensor network through several key features such as localized coordination and control for the CHs, local compression and randomized rotation of the CHs. The operation of LEACH is divided into rounds (a predefined interval of time during which cluster and inter-cluster communication takes place) and each round begins with a cluster set-up phase preceded by a steady-state phase where data transfer to the base station occurs. The set-up phase is organized as follows:

The advertisement phase – each node individually decides if it becomes a cluster head based on a suggested percentage (P) of cluster heads determined a priori as well as based on the number of times the node has been cluster head so far. By choosing a random number between 0 and 1 the node (n) can elect itself as cluster head if this number is less than a threshold $T(n)$ calculated as follows [5]:

$$T(n) = \begin{cases} \frac{P}{1-P*(r* mod \frac{1}{P})} & if\ n \in G \\ 0 & otherwise \end{cases} \quad (1)$$

where r is the current round and G is the set of nodes that have not been cluster heads in the last $\frac{1}{P}$ rounds.

After each round the probability of the remaining nodes must increase since there are fewer nodes eligible to become cluster heads.

Cluster set-up phase – after the cluster heads have been elected, each of them informs neighboring nodes so that each node decides the appropriate cluster head to attend to, based on the received strength of the cluster head advertisement.

Inter cluster communication – each CH creates a TDMA schedule and informs each node from the cluster when to communicate acquired data. To avoid interference with neighboring clusters, each CH also randomly chooses a CDMA code from a list of codes and informs all nodes in the cluster to use the given code.

For simulation purposes the authors of LEACH [5] have chosen the first order radio model where the radio dissipates $E_{elec} = 50\, nJ/bit$ to run the transceiver circuit, $E_{amp} = 100\, pJ/bit/m^2$ for the transmit amplifier and $E_{DA} = 5\mu J/bit$ for data aggregation and fusion. CHs collect k-bit long messages from attending n nodes and compress the data using a compression coefficient c, thus resulting in $c \cdot n$ k-bit messages sent to the BS. A path loss coefficient, $\alpha = 2$, has been considered for each communication. All nodes have the same energy in the beginning, $E_0 = 50mJ$. Thus the energy needed to transmit a k-bit long message over distance d is [5]:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$
$$E_{Tx}(k,d) = E_{elec} * k + e_{amp} * k * d^2 \quad (2)$$

The energy required to receive a message is:

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

Also, the maximum communication range of sensor nodes is 100 meters.

The steady-state (data transmission) phase – all nodes transmit sensed data to the elected CH according to the TDMA schedule they have received. After a certain time determined a priori the next round begins and the protocol resumes from the advertisement phase.

One significant disadvantage when using LEACH is that electing CHs the way previously described does not provide an even distribution of the CHs among the OA. This downside has also been observed by the authors of the MSD protocol which have come up with a solution which we will further describe.

B. The MSD and IMSD protocols

Hansen et al. [8] argue that there should be a minimum separation distance between the CHs in order to provide an even distribution of the CHs throughout the network. In order to test the impact of using a minimum separation distance between the elected CHs the authors have devised an algorithm briefly described Figure 1 [8].

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MSD = Minimum Separation Distance
dc = Number of desired cluster heads
energy(n) = Remaining energy for node n
avg = ∑ energy(n) / number of alive nodes
eligible = {n| energy(n) ≥ avg}
assert (|eligible| ≥ dc)
CD = {}
while (|CH| < dc)
    if ∃n: n ∈ eligible Λ (∀ m ∈ CH, dist (m,n)) ≥ MSD
        add (n, CH)
        remove (n, eligible)
    else
        n ∈ eligible
        add (n, CH)
        remove (n, eligible)
    end
end
```

Figure 1. MSD algorithm proposed by Hansen et al. [8]

Their algorithm is based on a variant of LEACH, LEACH-C (Centralized) meaning that the algorithm for the cluster head election is performed by the BS which informs each node in the network about the elected CHs for the current round. In turn, all nodes are obliged to inform the BS about their position information and current energy level each round. Based on this information the BS runs the algorithm and determines which nodes are eligible for becoming CHs for the current round by calculating the average energy remaining in the network. Only nodes with remaining energy above the average threshold become eligible for being CHs for that round. After determining the eligible nodes, CHs are randomly elected based on the minimum separation distance criterion until the desired number is attained. If this number cannot be obtained, random nodes are chosen from the remaining eligible nodes to perform the CH role. After the algorithm has been successfully executed, the elected CHs are informed by the BS of their new status and clusters are formed. Until the next round when the process is repeated the network performs communication the same way as in LEACH.

Simulations have been performed by the authors on a 400x400 meter network and the results have shown that depending on the number of desired CHs, using the MSD protocol results in increased number of messages received by the BS with up to 80% when compared to LEACH.

A more recent research by Chalak et al. [9] proposes an Improved MSD (IMSD) algorithm that solves the MSD issue when the desired number of CHs cannot be obtained without electing CHs that do not obey the minimum separation distance criterion.

To solve this issue the authors claim that the smallest distance allowed between two distinct CHs is the minimum separation distance, which can be smaller than a desired separation distance but should not be larger. If the desired number of CHs cannot be obtained the minimum separation distance is reduced by a pre-defined percentage and the algorithm is implemented again until the number of CHs is obtained. Using this method improvements are obtained compared to the MSD algorithm in terms of network lifetime and overall packet delivery.

Through simulations we have observed that by using either of these two algorithms the desired number of CHs is constantly maintained. An advantage of IMSD over MSD is that the CHs are more evenly spread over the entire area. The eligibility criterion employed by both algorithms gives network nodes equal possibilities to become CHs thus distributing the network load among all nodes. This practically means that the vast majority of nodes will remain without energy at about the same time.

We consider that CHs should be elected also based on other criterions such as the number of neighboring nodes in the area defined by the separation distance and also based on the size of the packet with respect to the allowed maximum size as most WSNs are event driven and modify the transmitted packet size when an event occurs. As simulations presented in the next chapter show, choosing CHs this way can have significant impact on network lifetime and packet delivery.

Using a centralized approach such as LEACH-C can introduce several disadvantages such as nodes that are far away from the BS will have difficulties in sending their status to the BS. If this role is assumed by the CHs for the current round it will induce further strain on those nodes. Either way using a centralized approach will result in increased overhead and communication latency. We consider that a local approach can be more suited as the energy consuming task of sending and receiving messages will be replaced by local computations thus reducing latency and overhead. Also a local approach will allow for scalability in situations where the sensor network is spread over larger areas that extend over the communication range of a node with the BS.

III. PROPOSED ALGORITHM

To address the previously mentioned issues we have developed the LEACH-ASDLD algorithm which we will further describe.

LEACH-ASDLD is a round based protocol structured on 3 layers of communication:

- Layer 1 represents a neighborhood reconnaissance procedure during which, in the first round nodes inform neighbors of their position information and in all other rounds nodes that remain without energy or newly added nodes inform neighboring nodes of their new status.
- Layer 2 is reserved for sensing and data gathering by network nodes which perform only intra cluster communications based on the TDMA/CDMA proposed schemes.
- Layer 3 is restricted to inter cluster head and cluster head to BS communication.

The following assumptions are made about the network model:

- The network consists of 100 randomly deployed nodes.
- We have performed simulations on areas having sizes ranging from 50x50m to 200x200m with a variation step of 25x25m.
- We assume that knowledge of the observation area size is previously known.
- All nodes are homogeneous, with the same hardware and software architectures and the same battery power.
- Energy consumption constraints are as described in Section I at the description of the LEACH protocol.
- The network is noise and error free.
- Network nodes are synchronized (using an RT Clock for example).

Based on these assumptions we will next provide a more detailed description about the proposed algorithm which can be divided into 4 steps.

1) Neighborhood reconnaissance – each node broadcasts a message with its position if a localization device is present or a dummy message so that other nodes can calculate the distance between themselves and the sending node by using the received signal strength indicator (RSSI) method. This procedure is performed in a TDMA fashion previously defined and only during the first round. In all other rounds the time span for it is reduced and this time window will serve as advertisement space for nodes that do not have enough energy to perform their tasks any more or for newly added nodes to broadcast their position information.

2) Cluster set-up phase – as the size of the OA is known, defining the separation distance between the CHs will actually determine the number of clusters that will be formed each round. Based on the desired number of clusters we have calculated the separation distance between the CHs using the following formula:

$$SD = \sqrt{\frac{L^2}{N}} \tag{4}$$

For a given square OA of size LxL, the question posed is, if we want to fit N squares within the area, what is the side length of each square (SD). Where N is actually the desired number of CHs.

Using the distance information obtained from Step 1, each node will calculate the ratio between the number of nodes within the separation distance and the number of neighbors in its range. Also each node will calculate the ratio between the expected packet size and the maximum allowed payload size which is 127 bytes according to the IEEE Standard 802.15.4 [10]. Each node calculates a threshold value using the following formula:

$$Th = \left(\frac{E_r}{E_0}\right)\left(1 - \frac{N_{SD}}{N_R}\right)\left(1 - \frac{P_{crt}}{P_{max}}\right) \tag{5}$$

where E_r is the remaining energy, E_0 is the initial energy, N_{SD} represents the number of nodes in the separation distance, N_R the number of nodes in the sensing range, P_{crt} is the current payload and P_{max} is the maximum payload.

The CH election phase is performed as follows. Initially each node is eligible for becoming a CH if it has enough energy to perform this task. Each node will generate a random number and set a timer according to it. The node with the smallest timer value will be the first advertised CH. Depending on the network size and node sensing range, several CHs can be elected throughout the OA. Nodes that are closer to a CH than the separation distance cannot advertise themselves as CH. Nodes that are farther than the separation distance are still eligible and the node with the smallest T_h will elect itself as CH also using a timer. The procedure is repeated until the entire OA is covered and there are no eligible nodes left. Using the smallest T_h value for electing CHs means that nodes with larger number of neighbors in the separation distance have higher probabilities of electing themselves CH. Using the described method can have a significant impact on the overall message delivery and network lifetime as we will show in Section IV.

Steps 3 and 4, ***Inter cluster communication*** and ***The steady-state (data transmission)*** phases are performed the same way as specified by the LEACH algorithm (Section II).

IV. SIMULATION RESULTS

In order to determine the impact of the proposed algorithm on the network lifetime and message delivery, we have performed several simulations in different scenarios which we will describe in the following subsections.

A. Network lifetime

As previously mentioned, using an algorithm as MSD [8] or IMSD [9], where the CHs are chosen based on the maximum amount of remaining energy, the overall load of the network is evenly distributed among sensor nodes, which means that the vast majority of nodes will remain without energy at approximately the same time. In LEACH-ASDLD cluster heads are elected with the minimum threshold value, thus straining nodes in key places of the network. To determine the impact of LEACH-ASDLD over the IMSD algorithm in terms of network lifetime we have performed several Matlab simulations on random distributed networks over areas with different sizes that range from 50x50 meters to 200x200 meters with a step of 25x25 meters and a desired number of 10 CHs for each simulation. The results can be seen in Figure 2.

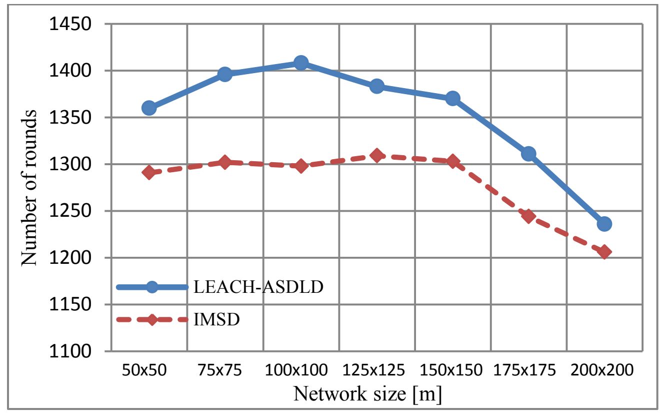

Figure 2. LEACH-ASDLD half nodes die vs. IMSD last node dies.

If we consider the first node dies (FND) metric IMSD outperforms our proposed algorithm, however if we consider the half node dies (HND) metric, as we can see from Figure 2, our proposed algorithm outperforms IMSD as when half of the nodes have died in LEACH-ASDLD, the entire network of nodes using the IMSD algorithm has already depleted all its energy. We can observe that by stressing key nodes in the network LEACH-ASDLD provides extended monitoring time of the OA when compared to the IMSD algorithm which is actually desired in a WSN.

An interesting behavior can be noticed in Figure 2. As mentioned in Section II, CHs serve the purpose of performing data aggregation and fusion operations. Also the maximum communication distance between sensor nodes is of 100 meters and the energy required to send a message is in direct correlation with the distance between the sender and receiver. Nodes send messages either directly to the BS or to the CHs, depending on which is closer. When both are within communication range, sending messages to the CHs can be more costly because of aggregation and fusion operations performed and this behavior can be noticed in Figure 2. This behavior can be avoided by electing the appropriate number of CHs per round depending on network size, however this optimization type is not of the purpose of this paper.

B. Message delivery

To determine the impact of the proposed algorithm on the overall message delivery of the network we have performed several simulations in different scenarios which we will further describe.

1) Different network sizes

We have performed simulations on randomly deployed WSNs over square areas of different sizes ranging from 50x50 meters to 200x200 meters with a variation of 25x25 meters. The packet size has been considered static (200 bits/packet) and each node sends a total of 20 packets per round. The number of desired CHs elected per round was 10. The results can be seen in Figure 3.

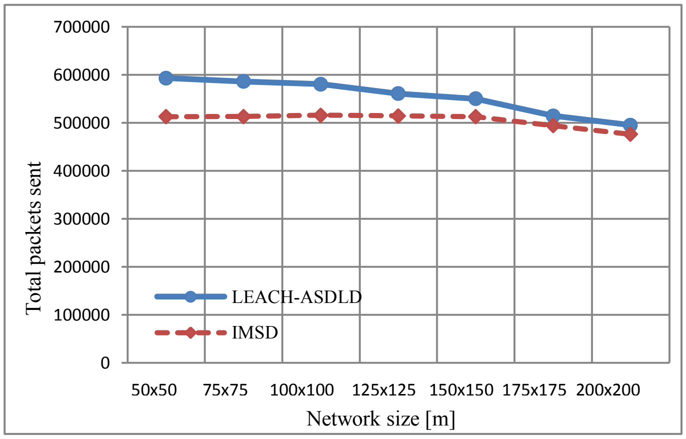

Figure 3. LEACH-ASDLD vs. IMSD – total number of packets sent for different network sizes

As can be seen from Figure 3, there is an increase of packets sent in the network dependent on the size of the OA that ranges from 15% for the 50x50 meters network to 4 % for the 200x200 meters network. This however can be an issue of electing the correct number of CHs as can be seen in the next section.

2) Different number of CHs

Electing the optimum number of CHs is another important research direction in the field of WSNs but it does not represent the purpose of this paper. To determine the performance of the proposed algorithm we have performed simulations on a 100x100 meters network with a different number of CHs ranging from 3 to 10 and the obtained results can be observed in Figure 4.

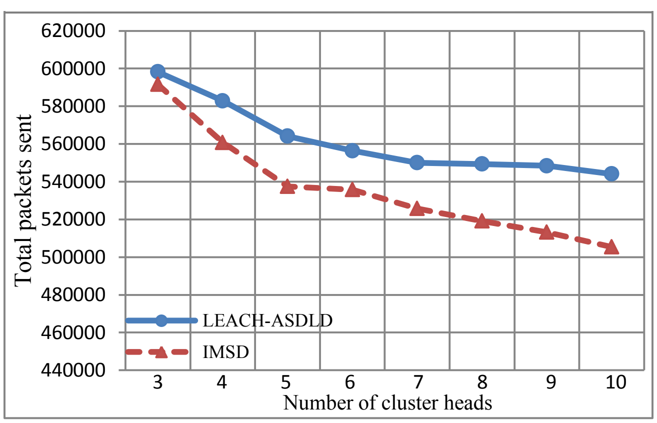

Figure 4. LEACH-ASDLD vs. IMSD – total number of packets sent for different number of CHs

We can see from Figure 4 that varying the number of CHs can have a significant importance over the message delivery of the entire network. Both protocols obtain the highest number of messages delivered for 3 proposed CHs and our proposed algorithm provides only a small improvement of 2% in terms of more messages transmitted. However as the number of CHs is increased LEACH-ASDLD obtains better performance with a maximum of 13% more packets for 10 elected CHs.

3) Different packet sizes

In order to determine the impact of the presence of an event in the network which would require an increase in the amount of communicated data we have spread the OA into 4 quadrants, the same as in the Cartesian coordinate system. For a specified number of 300 rounds we have increased the packet size from 200 with a specified percentage (25, 50, 75 and 100) in quadrants 2 and 4 while maintaining the OA at a fixed size of 100x100 meters. During our simulations we have observed that using the IMSD protocol when there is an increase in packet size, due to the election method of the CHs in which only nodes with remaining energy level above the network average are eligible for becoming CHs, the area in which the event takes place is left without any CH, which is not the case in LEACH-ASDLD. We have also noticed through simulation tryouts that increasing the number of CHs in these regions can lead to increased packet delivery as can be seen in Figure 5.

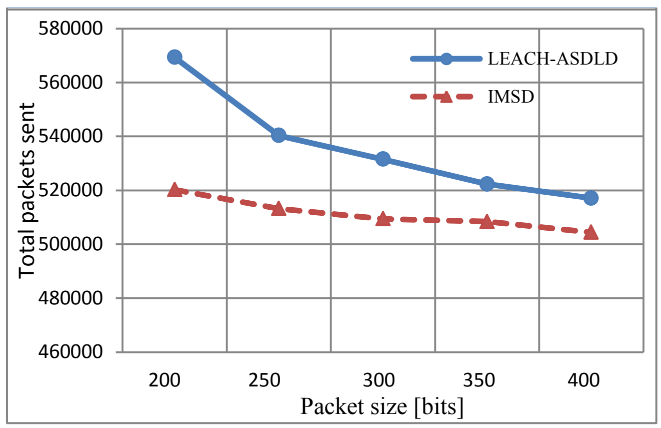

Figure 5. LEACH-ASDLD vs. IMSD – total number of packets sent for different packet sizes

The number of CHs within a certain region can be increased by using an adaptive minimum separation distance with respect to the packet size. We have obtained the best results for the current network distribution by reduced the minimum separation distance with a percentage of 7 (for the 250 bits packet) to 28% (for the 400 bits packet) with a step of 7%. However we have yet to find a direct correlation between optimum number of CHs and the number of nodes in the region/packet size. The obtained results show an increase in packet delivery that ranges from 7% for the 250 bits packet size to 3% for the 400 bits packet size when comparing LEACH-ASDLD with IMSD.

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V. CONCLUSIONS AND FUTURE WORK

In this paper we have described a proposed algorithm based on LEACH, LEACH-ASDLD that considers adaptive separation distance between CHs based on the expected packet size and also performs the election of CHs using information about surrounding nodes. We have performed simulations in various network distributions and conditions which we have compared with an improvement to LEACH that also considers a separation distance between CHs, IMSD.

Our simulation results have shown that further improvements can be obtained in terms of network lifetime and messages transmitted throughout the entire network. We have shown that using the proposed method in which key nodes are selected as CHs rather than evenly distributing the energy consumption throughout network nodes can provide extended network lifetime when using the HND metric. Also, the number of packets sent is increased by a factor of 4 to 15% depending on network size, 2 to 13 % depending on the number of desired CHs and 3 to 7% in correspondence with the packet size.

We have also argued that using a centralized protocol such as LEACH-C where network nodes have to inform the BS each round about their status can induce latency and overhead and also does not allow for scalability of the network. Our approach solves the problem of scalability by introducing a time slot in which newly added nodes but also nodes that do not have enough energy can inform neighboring nodes of their status. Using this local information approach expels the need for sending messages over long distances and reduces overhead. There are also several downsides to using our method such as it may require more time before all CHs are elected and also the number of CHs per round is not as stable as when using a centralized approach but will vary slightly (we have observed a maximum variation of $\pm$ 10% obtained for 10 desired CHs).

Future work includes determining a correlation between the packet size and the number of CHs (separation distance) as the size of the packet is increased. Also other metrics should be taken into consideration when electing the CHs such as packet frequency variation, expected throughput etc. The energy model used is incomplete and strictly refers to the send/receive of packets and data aggregation/fusion operations performed by cluster heads. This issue should also be improved and other energetic aspects should be taken into consideration such as the power consumed by the microcontroller in different working modes, energy for communication with peripheral devices (sensors), transceiver on/off etc.

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