Lecture Notes in Networks and Systems 371

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Intelligent Computing & Optimization

Proceedings of the 4th International Conference on Intelligent Computing and Optimization 2021 (ICO2021)

Springer

Towards Energy Savings in Cluster-Based Routing for Wireless Sensor Networks

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Abstract. Wireless Sensor Networks (WSNs) are mainly composed of a number of Sensor Nodes (SNs) that gather data from their physical surroundings and transmit it to the Base Station (BS). These sensors, however, have several limitations, including limited memory, limited computational capability, relatively limited processing capacity, and most crucially limited battery power. Upon these restricted resources, clustering techniques are mainly utilized to reduce the energy consumption of WSNs and consequently enhance their performance. The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol serves as a good benchmark for clustering techniques in WSNs. Despite LEACH retains energy from sensor nodes, its energy efficiency is still considerably compromised due to unpredictable and faster power draining. Therefore, the goal of this paper focuses on how the LEACH protocol may be used effectively in the field of environmental monitoring systems to address issues about energy consumption, efficiency, stability, and throughput in a realistic simulation environment. The realistic performance analysis and parameter tuning were carried out utilizing the OMNET++/Castalia Simulator to serve as a baseline for future developments.

Keywords: WSNs · LEACH · Clustering · Energy efficiency · OMNET · Castalia

1 Introduction

Recently, Wireless sensor networks (WSNs) have been regarded as a significant research area due to their critical involvement in a variety of applications. Wireless sensor nodes collect data, analyze it for optimization, and then send it to the sink via a network of intermediary nodes. The network of these nodes as a whole constitutes the wireless sensor network, which is capable of organizing data and transmitting it to the requester (sink) [1]. Meanwhile, energy efficiency is still a critical problem in the design of WSN's routing protocol according to resource constraints and the non-rechargeability of resources for sensor nodes [2, 3].

Notably, clustering approach is widely used approach for managing the topology of WSNs, since it may significantly enhance the network's performance. It can make nodes in groups according to predefined criteria such as ensuring QoS, optimizing resource requirements, and balancing network load. A leader node which manages each cluster is called Cluster Head (CH). This node is responsible for data collection from

P. Vasant et al. (Eds.): ICO 2021, LNNS 371, pp. 407–416, 2022.
https://doi.org/10.1007/978-3-030-93247-3_40

cluster members (CMs) and transmitting it to the Base Station. Clustering techniques eliminate the need for resource-constrained nodes to transfer data directly to gateways (sinks), which results in energy depletion, inefficient resource utilization, and interference.

Numerous studies on energy efficiency and data collection for cluster-based routing algorithms have been conducted [4–7]. The most of these strategies consist of two phases: (i) Setup phase and (ii) Steady-State phase. The first phase involves the selection and formation of CHs, as well as the assignment of a TDMA schedule to member nodes by the CH [8]. Meanwhile, the former phase is responsible for transmitting the identifiable data to their CHs via a specified TDMA slot allocated by the setup phase's CH. Then, the CHs collect the data from CMs and transfer it to the Base Station.

Several LEACH, PEGASIS, TEEN, APTEEN, and HEED protocols [9–12] are devoted as the primary hierarchical routing protocols in WSN. Each has numerous variants that are adapted to certain applications.

Typically, the Sensor Nodes (SNs) consume a great deal of energy during data transmission rather than data processing. As a result, it is critical to minimize redundant sensed data transmission to the BS through the efficient deployment of Cluster Heads (CHs) in a network. Hence, it is important to evaluate the routing protocol in major aspects and scenarios to guarantee the real-world design of WSNs and ensure optimal environment simulation for further improvement utilizing a variety of optimization methods.

In this paper, the LEACH protocol is evaluated as a good benchmark for a single-hop clustering algorithms. Numerous scenarios are presented to evaluate the overall energy efficiency and throughput. Moreover, in order to find the typical values for each scenario, several parameters are considered, including the optimal CHs percentage, packets received by the Sink (BS) located in various locations under various node density and data rates. Extensive simulation demonstrates that once the node density of the same area size increases, the network's energy consumption decreases, resulting in extending the network lifetime of a WSN. Additionally, it is observed that when the CH percentage is optimal, the energy consumption of a network is minimal. However, when the CH percentage of a network exceeds an optimal value, energy consumption increases, significantly reducing the network's lifetime.

The rest of this paper will be structured as follows. Firstly, the literature review is addressed in Sect. 2. In Sect. 3 the LEACH protocol is described in detail. Meanwhile, in Sect. 4 the network model is discussed. Section 5 displays and discusses the simulation results. Finally, in Sect. 6, the conclusion has been drawn.

2 Related Works

"The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [13] is one of the most well-known protocols. It makes use of energy consumption by employing adaptive clustering via its advantage as a good benchmark for clustering routing protocols in WSNs and MANETs. Within LEACH, the nodes in the network field are clustered and established. Each cluster has a single leader node identified as the cluster head (CH), and this node is selected at random manner. Moreover, while the LEACH protocol retains energy from sensor nodes, its energy efficiency is likely impacted by random and fast energy dissipation, which is increased by the cluster's unequal distribution of nodes and the time restriction imposed by the TDMA MAC Protocol [13–15].

In LEACH protocol, the CHs are randomly assigned to operate as relay nodes for data transmission; afterward, the cluster heads shift roles with regular nodes to spend a uniform amount of energy in all nodes. The suggested hybrid approach extends the lifetime of nodes while decreasing the energy consumption of the transmission. Numerous research have recently examined the routing and energy consumption challenges related to LEACH protocol by modifying the mathematics models to increase overall performance using a variety of efficient ways [16, 17]. Meanwhile, intelligent algorithms [18–22] are also used as a viable strategy for lowering the energy consumption of WSNs and extending the network's lifetime. Furthermore, other researchers have stressed the critical role of Fuzzy Logic System (FLS) in the decision-making process for CH efficiency in WSNs [23]. All these studies emphasize on the predefined protocol with specific parameters that affect the efficiency of the optimized LEACH protocol's routing. Such parameters include the sensor node's life time, the total number of packets received, the latency of the transmission, and the scalability of the number of sensor nodes.

Nevertheless, most works evaluated their proposed protocols in a virtual environment without examining the effect of the original protocol's parameters on the network's efficiency. Thus it is critical to evaluate the routing protocol in major aspects and scenarios using realistic simulation environments such as Castalia and OMNET++ Simulator. This technique ensures that WSNs are designed in the actual world environment and provides a realistic implementation for further development of the LEACH protocol and its versions (LEACH-C, M-LEACH,…etc.) using various optimization techniques.

3 Low Energy Adaptive Clustering Hierarchy Protocol

LEACH is a pioneering WSN clustering routing protocol. LEACH Protocol's major purpose is to enhance energy efficiency by random CH selection. LEACH is operated in rounds that consist of two phases: Set-Up Phase and Steady-State Phase. Clusters are constructed and a cluster head (CH) is elected for each cluster during the setup phase. Meanwhile, during the steady phase, the data is detected, aggregated, compressed, and transmitted to the base station.

i. **Set-Up Phase:** The Set-Up step involves the selection and construction of CHs, as well as the assignment of a TDMA schedule to member nodes.

   1. **Cluster Head Selection:** Each node assists in the process of CH selection by randomly creating a value between (0 and 1). If the random number generated by the SN is smaller than the threshold value T (n), the node becomes CH, else it considers as CM and waits for ADV messages to join the nearby CH. Equation 1 is used to find the value of T (n).

$$T(n) = \begin{cases} \frac{P}{1-P(r \bmod 1/P)} & \text{if } n \in G \\ 0 & \text{Otherwise} \end{cases} \tag{1}$$

Where: P is the percentage of the CHs, which is used at the beginning of each round (starting at time t), such that expected the number of CHs nodes for this round is K.

$$P = K/N \tag{2}$$

2. **Cluster Formation:** Once the CHs are elected, they broadcast ADV messages to the rest of the sensors using CSMA MAC protocol. Non-CHs must maintain their receivers throughout the Set-Up phase to hear all CHs' ADV messages. After this phase is complete, each sensor determines which cluster it belongs to based on the RSSI value. Meanwhile, each sensor node (SN) transmits JOIN-REQ messages to its corresponding CH using CSMA.
3. **Schedule Creation:** Each CH node generates a TDMA schedule based on the number of JOINT-REQ messages received. The schedule is broadcast back to the cluster's nodes to inform them when they can transmit.

ii. **Steady-State Phase:** The steady-state or transmission phase is where environmental reports are communicated from the network field. During this phase, each sensor node transmits its data to the CH during its assigned time slot (intra-cluster communication), meanwhile, each CH aggregated the data from the corresponding CMs and sent it to the BS (inter-cluster communication).

The key advantages and limitations of the LEACH protocol can be summarized as follow (Table 1):

4 Network Model

The following criteria are considered when describing the network model based on the proposed protocol:

1. Sensor Nodes are uniformly distributed across a M $\times$ M interesting area, and throughout the process, all nodes and the BS remain stationary (non-mobile).
2. Each sensor node is capable of sensing, aggregating, and transmitting data to and from the base station (BS) and other sensors (i.e., acts as a sink node).
3. The network's nodes are non rechargeable and have homogeneous initial energy.
4. To ensure optimal performance, the Sink Node (BS) is positioned in the network field's center. Quite frequently, the assumption is made that the communication links between the nodes are symmetrical. As a result, when it comes to packet transmission, any two nodes' data rate and energy consumption are symmetrical.
5. The nodes operate in power control mode, with the output power determined by the receiving distance between them.

Table 1. Advantages and Limitations of LEACH protocol.

Advantages	Limitations
▪ The clustering technique used by the LEACH protocol results in decreased communication between the sensor network and the BS, extending the network's lifetime	▪ Expansion of the network may result in a trade-off between the energy distances of a CH and a BS
▪ CH utilizes a data aggregation technique to reduce associated data on a local level, resulting in a significant reduction in energy consumption	▪ Due to the random number principle, nodes do not resurrect to become CHs, which further reduces their energy efficiency
▪ Each sensor node has a reasonable chance of becoming the CH and subsequently a member node. This maximizes the lifetime of the network	▪ No consideration is made of heterogeneity in terms of energy computational capabilities and link reliability
▪ By utilizing TDMA Scheduling, intra-cluster collisions are avoided, extending the battery life of sensor nodes	▪ The TDMA approach imposes constraints on each frame's time slot

5 Simulation Results and Performance Analysis

This section discusses the LEACH's performance evaluation. The LEACH protocol is examined when a network of 100 sensor nodes is uniformly distributed over a 100 x 100 m^2 area. The BS is positioned in the sensor field's center. All nodes should have initial energy of 3 J. Moreover, we used around the time of 20 s in our scenarios with a maximum simulation time equal to 300 s. The size of all data messages is the same and the slot time is utilized to 0.5 in all simulation situations. The total overview of simulation parameters is shown in Table 2.

Table 2. Simulation parameters.

Parameters	Value	Parameters	Value
Network size	100 × 100 m^2	Initial energy	3 J
No. of nodes	100	Simulation time	300 s
No. of clusters	5	Round time	20 s
Location of BS	50 × 50 m		
Node distribution	Uniform	Packet header size	25 Bytes
BS mobility	Off	Data packet size	2000 Bytes
Energy model	Battery	Bandwidth	1 Mbps
Application ID	Throughput test		

5.1 Performance Evaluation of LEACH Protocol

In this section, numerous factors are considered when evaluating Low Energy Adaptive Clustering, including the number of nodes, the CH percentage, and the area size. The LEACH protocol's performance is quantified in term of the total energy consumed by sensor nodes during each round for data processing and communication. Also, reliability is another metric evaluated by the total number of received data packets.

Experimental Case I

Figures 1 and 2 depict the effect of node density (number of nodes per m^2) and area size on energy consumption. Where (50, 100, 200) sensor nodes are uniformly distributed across 100×100 m^2 and 200×200 m^2 areas, respectively. Each node has initial energy of 3J, with a CH percentage of 5%. If the CH percentage remains constant but the network's node density increases, this results in an increase in the number of CHs in the network proportional to the network's node density. The energy consumption of nodes is minimal at CH = 5% of 100×100 m^2 area networks with 100 nodes (5 CHs selected), and minimal at 200 nodes (10 CHs selected) of 200×200 m^2 network. This is because as the coverage area increases, the node consumes more energy transmitting the sensed information to the sink with the fewest CHs possible.

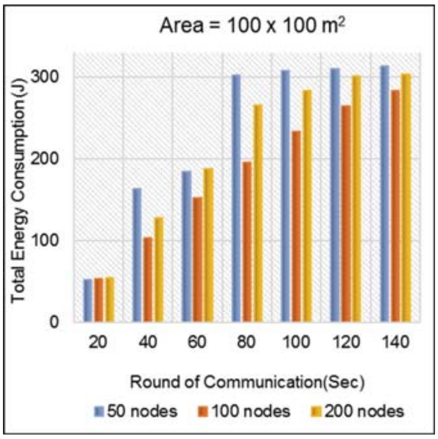


Fig. 1. Total energy consumption

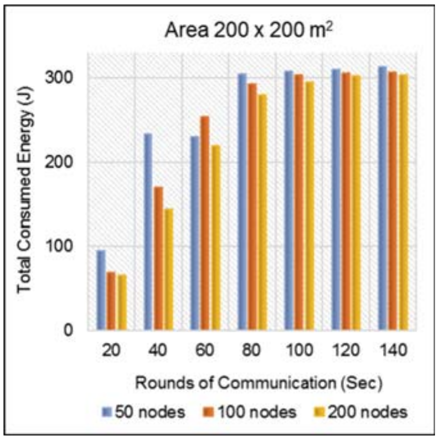


Fig. 2. Total energy consumption

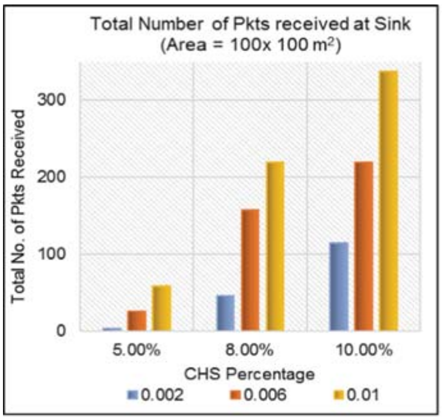
In Fig. 1, it is shown that when the CH percentage is optimal, the energy consumption of a network becomes minimal. However, when the CH percentage of a network exceeds an optimal value, energy consumption increases, significantly reducing the network's lifetime. So that it's important to choose the optimal value of the CHs percentage to avoid extra power consumption from the sensor nodes.

Experimental Case II

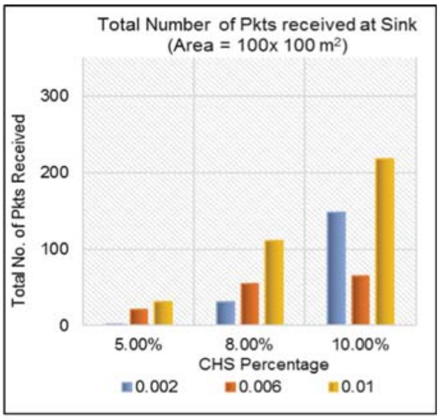
Figures 3 (a–d) illustrate the effect of node density (number of sensor nodes per m^2), area size, and packet rates expressed as a percentage of CHs on the total number of packets received at the sink. The network is configured as in Table 3:

Table 3. Network Configuration.

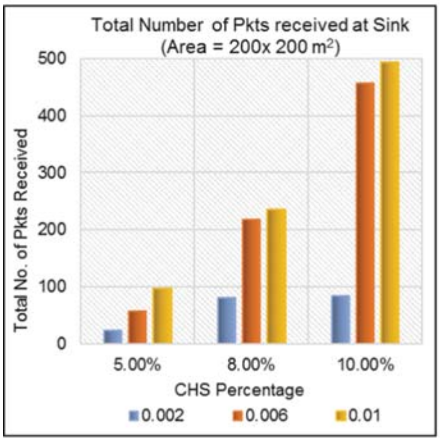
Area (m^2)	Node density	No. of nodes	CH percentage	Packet rate
100×100	0.002	20	5%, 8%, 10%	1, 3
	0.006	60		
	0.01	100		
200×200	0.002	80	5%, 8%, 10%	1, 3
	0.006	240		
	0.01	400		



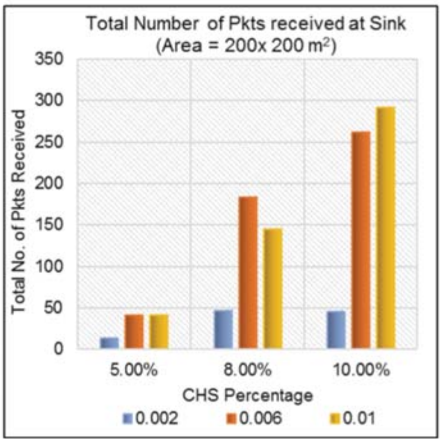
(a) packet rate = 1 packet/sec/node.



(b) packet rate = 3 packet/sec/node.



(c) packet rate = 1 packet/sec/node.



(d) packet rate = 3 packet/sec/node.

Fig. 3. (a–d): The effect of node density, area size, and the packet rates with CHs percentage on the total number of packets received at the sink

In Figs. 3 (a–d), the obtained results illustrate that increasing the packet rate results in a decrease in the network's packet reception rate, this occurs due to increased CH congestion. Increased packet rate enables source sensor nodes to relay the sensed data more quickly to their CHs during their assigned time slot. CH is now receiving more packets from its associated sensor nodes than it is broadcasting to a sink as a result of this increase in the packet rate. In effect, the Congestion arises in the WSN as a result of this condition. Thereby, the sensor buffer begins to overflow, increasing packet loss and lowering the rate at which packets are received in the WSN.

6 Conclusions and Discussion

The Low Energy Adaptive Clustering Hierarchy (LEACH) is evaluated with many considerations, including node density, CH percentage, packet rates, and Area size.

As seen from the findings, the CH percentage remains constant but the network's node density increases. This results in an increase in the number of CHs in the network proportional to the network's node number. Moreover, when the CH percentage is optimal, the energy consumption of a network is minimal. However, when the CH percentage of a network exceeds an optimal value, energy consumption increases, significantly reducing the network's lifetime. So that it's important to choose the optimal value of the CHs percentage to avoid extra power consumption from the sensor nodes. The energy consumption of nodes is minimal at CH = 5% of $100 \times 100\ m^2$ area networks with 100 nodes (5 CHs selected), and minimal at 200 nodes (10 CHs selected) of $200 \times 200\ m^2$ network. This is because as the coverage area increases, the node consumes more energy transmitting the sensed information to the sink with the fewest CHs possible. As the number of CHs increases, the amount of energy consumed is reduced proportionately.

In addition, the obtained results also illustrate that increasing the packet rate can cause in a decrease in the network's packet reception rate due to the increase in CH congestion. Note that once packet rate is increased this would enable source sensor nodes relay the sensed data more quickly to their CHs during their assigned time slot. CH is now receiving more packets from its associated sensor nodes than it is broadcasting to a sink, then this may increase the packet rate. As a result, Congestion arises in the WSN and the sensor buffer begins to overflow. This means that packet loss becomes high and a significant reduction happens in the resultant packet rate during packets delivery in the WSN.

For future work, fuzzy logic systems and intelligent algorithms such as FPA, GWO, ACO, and ABC algorithms can be utilized to improve the routing strategy in the LEACH protocol. Additionally, multi-hop routing techniques can be also considered for optimal monitoring system design.

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