# Reliable and energy-efficient multi-hop LEACH-based clustering protocol for wireless sensor networks 

Sara Al-Sodairi ${ }^{\mathrm{a}, \mathrm{b}}$, Ridha Ouni ${ }^{\mathrm{a}, *}$<br>${ }^{\text {a }}$ College of Computer and Information Sciences, King Saud University, KSA<br>${ }^{\text {b }}$ College of Computer and Information Sciences, Princess Nourah bint Abdul Rahman University, KSA

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#### Abstract

Wireless sensor networks (WSNs) are attracting research attention because of their important applications in critical environmental monitoring and target tracking in both civilian and military fields. The large-scale deployment of energy-constrained WSNs and the need for multi-hop data aggregation requires efficient organization of network topology to simplify the routing task, balance the load, and prolong the network lifetime. Clustering has proven to be an effective approach for organizing the network into a connected hierarchy. In this study, we analyze the effectiveness of low-energy adaptive clustering hierarchy (LEACH) and LEACH-based protocols in extending the lifetime for energy-constrained WSNs. An improved LEACH clustering protocol called enhanced multi-hop LEACH is proposed to reduce and balance energy consumption in order to allow increased packet delivery and network lifetime in WSNs. Additionally, this paper presents the weaknesses of the LEACH protocol. First, we introduce new rules for cluster-head selection and round time computing based on the remaining energy. Second, a multihop communication model is integrated in the WSN using two operating processes: leveling and generic multi-hop routing. © 2018 Published by Elsevier Inc.


## 1. Introduction

Wireless Sensor Networks (WSNs) have been widely considered to be one of the most important technologies of the twentyfirst century [1]. It has a wide range of ever-increasing important applications. The sensor nodes are tiny and cheap; they are batterypowered devices that are deployed in a physical area to collect useful information and transmit it through wireless links to sink nodes. These sensors can communicate either among each other or directly to the sink. However, nodes have limited energy resources that represent the biggest challenge for WSNs. The energy efficiency, robust self-organization, clustering, and routing protocols are very important aspects of conserving energy and prolonging network lifetime, while ensuring proper operations of the network. Moreover, WSNs present some weaknesses because of their limited buffering features and computational resources.

The main problem in WSNs is controlling energy consumption across the whole network. The limitation of energy resources is

[^0]a major issue in every wireless device. This issue is particularly amplified in WSNs for the following reasons [2].

- A WSN comprises many nodes. Therefore, recharging or replacing batteries is almost impossible.
- WSNs may be deployed to inaccessible places.
- The size of nodes is very small.
- Nodes are responsible for complex tasks such as sensing, processing, self-organizing, and communication.
- The failure of a few nodes leads to the manifestation of independent clusters.

For these reasons, network lifetime constitutes a crucial factor in WSNs, requiring more investigation before improvement. A new coherent clustering algorithm should fairly distribute energy consumption in the entire network by the following means.

- Develop a new clustering algorithm that dynamically distributes the operating tasks among sensor nodes (e.g., cluster head (CH), relay, regular). These nodes periodically change their operating modes to ensure equitable energy consumption and to improve the network lifetime.
- Regarding the low-energy adaptive clustering hierarchy (LEACH)-based clustering algorithm, a new multi-hop-based
process between CHs can conserve their residual energies. A leveling phase should first be introduced to attribute different levels for all sensor nodes according to their distances from the sink node.
- The amounts of residual energies should be used to make the decision on how to control the energy distribution for the entire network. Thus, calculating the round time, based on energy consumption in the network, leads to fair energy distribution among all nodes, because CHs change in each round.

The main objective of this paper consists of combining these contributions in a coherent algorithm that (a) considers the available resources and (b) improves the lifetime and reliability of the WSN. The rest of the paper is organized as follows. Section 2 presents energy efficiency protocols that consider LEACH protocol and several related works as enhanced LEACH-based clustering protocols. Section 3 describes the technical processes of a new enhanced LEACH-based algorithm for more energy efficiency. Section 4 presents the simulation environment and outlines the obtained results evaluating the algorithm performance. Section 5 concludes the achieved work.

## 2. Energy efficiency protocols

Energy consumption is caused by three activities: sensing, data processing, and communications. Communication energy constitutes the major part of the consumed energy in the wireless device, whereas energy optimization focuses on the radio module operating modes [3]. The communication energy is defined in [4] as the sum of the data transmission energy (i.e., transceiver energy) and the data processing energy. WSNs should operate with optimal energy to increase the lifetime of the sensor nodes, simultaneously ensuring network connectivity and availability. Because of the scarcity of energy in WSNs, energy optimization is needed to minimize the energy consumed by the sensor nodes to prolong network lifetime. Thus, energy efficiency must be considered in every aspect of network design and operation, for both operation of the individual sensor nodes and communication of the overall network [5].

### 2.1. LEACH protocol

The LEACH protocol is considered the first clustering-based routing protocol to achieve scalable solutions and extend network lifetime [6]. LEACH allows minimization of global energy usage by continuously distributing the network load to all nodes at different points. Typically, sensor nodes are organized hierarchically in clusters, including a CH for each. The CH is responsible for gathering data from nodes of its group, aggregating data reports, and routing them to the sink node. Using LEACH, a node is elected to CH when its probability, defined by a random number chosen between 0 and 1 , is less than a specific threshold, $T(n)$ (Eq. (1)). The rest of the nodes join a certain cluster by choosing the CH that can be reached with the least communication energy. The role of CH rotates all the sensors to prevent draining the battery of a single sensor.
$T(n)= \begin{cases}\frac{\rho}{1-\rho *\left(r * \bmod \frac{1}{\rho}\right)}, & \text { if } n \varepsilon G \\ 0, & \text { otherwise }\end{cases}$
Where $\rho$ is the desired percentage of $\mathrm{CHs}, r$ is the current round, and $G$ is the set of nodes that have not been cluster-heads in the last $1 / \rho$ rounds.

The operation of LEACH is divided into rounds, each starting with a setup phase to organize nodes into clusters, followed by a steady-state phase, responsible for data transfers to the sink node.

To minimize overhead, the steady-state phase is long-compared to the setup phase. During the setup phase, once a node decides to become a CH , it broadcasts an advertisement message using carriersense multiple access (CSMA) as media access control protocol. Upon reception of this message, each non-cluster node will decide to join a certain CH , depending on the received signal strength (RSS). The CH creates a time division multiple access (TDMA)-based transmission schedule for each node in the cluster. In the steady-state phase, each member node transmits data during its own timeslot and reduces energy consumption by entering sleep mode during the remaining timeslots. The CH aggregates the data received from various nodes inside the cluster and sends them to the sink. LEACH is completely distributed, requiring no control information from the sink, and nodes do not require knowledge of the global network for LEACH operation.

The LEACH protocol is summarized by the following processes.

- Setup Phase
- Cluster-head election
- Cluster formation
- Steady-state phase
- Schedule Creation
- Data Transmission


### 2.2. Weaknesses of LEACH

LEACH protocol allows prolonging network lifetime. However, there are some weaknesses that can be addressed to improve the effectiveness of new LEACH-based protocols [7,8]. Some of these problems and their solutions are given below.

- LEACH assumes that all nodes can reach the sink, affecting the scalability of the protocol. This can be addressed by introducing multi-level clusters and supporting multi-hop routing.
- The overhead involved, because changes in CH, leads to energy inefficiency. This problem can be addressed by reducing the number of rounds in the cluster rebuilding phase.
- The probability of selecting CHs does not consider the remaining energy of nodes. Therefore, nodes with low remaining energy may be chosen as CHs , causing a fast energy loss of these nodes, and resulting in disconnection of the entire cluster.
- The number of CHs fluctuates heavily. This aspect leads to unbalanced cluster partitions, which increases the total energy dissipation of the entire network.


### 2.3. Related works: extended LEACH-based protocols

Owing to energy limitations within WSN nodes, it is essential to reduce power consumption to improve network lifetime and efficiency. Different studies have investigated the available options for reducing the energy consumption. Transmission power management, multi-hop communication, self-organization, and routing are concepts addressed most for this purpose. The LEACH protocol is the first cluster-based routing protocol for WSNs that uses stochastic modeling for CH selection. Various improvements have been made to the LEACH protocol, providing different routing protocols for WSNs [9]. In the following paragraphs, we describe some LEACH-based clustering protocols and their impacts on energy efficiency and multi-hop communications.

In [10], Loscri et al. proposed the two-level LEACH (TL-LEACH) algorithm as an extended version of LEACH, utilizing two levels of CHs (i.e., primary and secondary). The primary CH in each cluster communicates with the secondaries, and corresponding secondaries communicate with the nodes in their sub-clusters. The two-level structure of TL-LEACH reduces the number of nodes that need to transmit to the sink. Thus, it effectively reduces the total
energy usage. If using TL-LEACH, the number of rounds consumed when the first node dies (FND) is about 200 more than when using LEACH. The number consumed is near 500 rounds more when the last node dies (LND).

Multi-hop routing with LEACH (MR-LEACH) was proposed by Farooq et al. [11] to partition the network into different cluster layers. The CHs in each layer collaborate with the adjacent layers to transmit data to the sink. Other nodes join CHs, based on the RSS indicator (RSSI). The sink selects the upper layer CHs to act as super CHs for the lower layer CHs. The sink is also responsible of defining the TDMA schedule for each cluster-head to transmit data. Thus, MR-LEACH uses multi-hop routing starting from cluster-heads to the sink to save energy and increase network life.

Cell-LEACH, proposed by Yektaparast et al. [12], is an improvement to the LEACH protocol, where every cluster is divided into seven subsections called cells. Additionally, every cell has a cell-head that communicates directly with cluster-heads. They aggregate their cell information and prevent sensors from communicating.

Wang et al. [13] proposed a hybrid cluster-head selection LEACH (LEACH-H) as an improved version of the LEACH protocol. In the first round of LEACH-H, the sink deploys a simulated annealing algorithm to select the CH set. In the next rounds, each CH selects a new CH for its own cluster. Using this approach, the authors attempted to maintain the characteristics of cluster-head distribution, which caused the CHs to be evenly distributed in the network. This saved energy consumption and extended the network lifetime.

Guo et al. [14], proposed an adaptive CH election and two-hop LEACH (ACHTH-LEACH) protocol to increase the network lifetime. ACHTH-LEACH is an extended LEACH protocol, using an adaptive algorithm of CH election and multi-hop communication among CHs. Each node in the network is tagged as a "near" or "far" node, based on its distance from the sink. All near nodes are included in one cluster, whereas far nodes are divided into different clusters using the greedy K-means algorithm. Each round, the CH -shifting process elects the node with the maximal residual energy in each cluster. During the data transmission phase, the far CH may select the CH in the near area as the next hop, or they may communicate directly to the sink. ACHTH-LEACH effectively prolongs the life span of the network more than two-times over LEACH and build a more stable routing environment.

LEACH-balanced (LEACH-B) is another improved LEACH protocol. At each LEACH-B round, the first CH is selected using the same LEACH concept. Afterwards, a second selection is introduced to modify the number of CHs , considering the node's residual energy [7]. Thus, the number of CHs is constant and nearly optimal every round.

A new model of the LEACH's stochastic cluster-head selection algorithm was proposed [15] that added the remaining energy level to the probability of each node, further reducing and balancing the total energy dissipation of sensors. To ensure an even energy load distribution over the whole network [15], introduced two terms in the threshold, $T(n)$, equation. The first term represents the remaining energy rate, which will impact the CH selection and the desired percentage. The second term is the optimal cluster-head number, $k_{o p t}$, defined in [16].

Later, the authors in [17] analyzed the classic clustering routing algorithms, LEACH and LEACH-C, and outlined their main problems in terms of CH selection, unbalanced energy loads, and short lifetimes. They proposed a CH selection algorithm suitable to water-regime monitoring. This algorithm, LEACH-head expected frequency appraisal, is based on a CH expected frequency appraisal that balances the energy consumption of nodes in the WSN, rationalizes the clustering process, and effectively prolongs the network lifetime.

Additionally, LEACH-R was proposed to improve the efficiency of the CH selection process by choosing certain sensors as relay nodes [18]. LEACH-R considers the residual energy of the nodes as the main metric for cluster-head selection to avoid low-energy nodes being cluster-heads. Moreover, LEACH-R chooses relaying nodes based on both residual energy and distance to the sink node. These relaying nodes are chosen from CHs to forward packets between the sink node and other cluster-heads. LEACH-R protocol saves around $20 \%$ of the sensor network energy, compared to LEACH.

In [19], the authors proposed an adaptive and energy-efficient clustering algorithm for event-driven applications (AEEC), which aimed to prolong the lifetime of a sensor network by balancing energy usage of its nodes. It gives more chances for nodes and has more residual energy for CH selection. Additionally, it uses elector nodes for collecting energy information of the nearest sensor nodes and for selecting the CHs .

In [20], the E-LEACH algorithm proposed the original random selection method of CHs , characterized by a fixed round time. The E-LEACH algorithm considers residual power in the sensor nodes to balance the network load; it also changes the round time, depending on the optimal cluster size. The simulation results show a $40 \%$ network lifetime increase, compared to LEACH.

Improved LEACH (I-LEACH), proposed by Kumar and Kaur [21], was designed with two important changes. First, residual energy is used to select the CHs, rather than the probability, as deployed in LEACH. This concept works well with sensor nodes operating at different initial energies. Second, the I-LEACH uses coordinates for cluster formation to guarantee that at least one CH is close to every sensor node. LEACH protocol does not consider the CH location.

Multi-group-based LEACH (MG-LEACH) is a LEACH-based energy-efficient routing algorithm [22]. MG-LEACH aims to minimize redundancy in WSNs. Many redundant data are available in WSNs because of widely deployed nodes monitoring similar events. CHs discards the redundant information before forwarding it to the sink. MG-LEACH uses this redundancy of deployed nodes as an advantage for increasing network lifetime.

In [23], Enan Khaili et al. proposed an energy-aware evolutionary routing protocol based on evolutionary algorithms (EAERP). EAERP uses the formulation of the fitness function to find clustered routes that minimize the overall energy dissipated by the network. Over rounds, the individual energies of these CHs are expended earlier than in the other protocols, but in a spaced interval fashion. EAERP has been proven by simulation to be a meaningful way of deriving clustered routes with a better tradeoff between network stability and network lifetime, while guaranteeing a welldistributed energy consumption.

Improved cluster-based multi-hop LEACH routing was proposed as an improved multi-hop LEACH, using both inter-cluster as well as intra-cluster communications [24]. To improve connectivity, it elects, in each cluster, a node as a vice CH that will become CH when the CH dies. Simulation of the improved multi-hop LEACH showed that it can effectively increase network lifetime and reduce energy consumption in WSNs.

In [25], M. Aslam et al. presented a survey of extended LEACHbased clustering routing protocols for WSNs. These protocols are solar-aware LEACH, multi-hop LEACH, and mobile-LEACH. They compared the features and performance issues of these hierarchal routing protocols. Using analytical comparison and simulation results, they also compared their lifetime and data delivery characteristics.

The purpose of this literature survey is to examine energy efficiency and throughput enhancement of various related routing protocols. Table 1 summarizes our study of different extended LEACH-based clustering protocols. The LEACH-based clustering protocols we surveyed predominantly focused on task partition,

Table 1
Comparison of different extended LEACH-based protocols in WSNs.

| Protocol Name | Extensions | Cluster formation | Energy Efficiency | Connectivity | Performance improvements |
| :---: | :---: | :---: | :---: | :---: | :---: |
| TL-LEACH | - Uses two levels of CHs: primary and secondary. <br> - Primary CH communicates with secondaries, and corresponding secondaries communicate with the nodes in their sub-cluster. | Dynamic | Yes | Two-hops | - Reduce the number of nodes that need to transmit to the sink. Effectively reduce the total energy usage. |
| MR-LEACH | - Partition the network into different layers of clusters. <br> - Sink selects the upper layers' CHs to act as super CHs for lower layer CHs. <br> - Equal clustering. | Dynamic | Yes | Multi-hop | - Reduce energy consumption. |
| Cell-LEACH | - Every cluster is divided into seven cells. <br> - Cell-head communicates with CH directly. <br> - Consider residual energy for CH selection. | Static | Yes | Two-hops | - Reduce energy consumption. <br> - Increase network lifetime. |
| LEACH-H | - Use simulated annealing algorithm to select the CHs during the first round. <br> - The new CH is selected in its own cluster by the former CH . <br> - Maintain the number of clusters as optimal. | Dynamic | Yes | Single-hop | - Reduce energy consumption. <br> - Increase network lifetime. |
| ACHTH-LEACH | - Nodes are tagged as near or far nodes, depending on their distances to the sink. <br> - Near nodes are included in one cluster. <br> - Far nodes are divided into different clusters by the greedy K-means algorithm. <br> - Node with maximum residual energy in the cluster are selected as next CH for each cluster. | Dynamic | No | Multi-hop | - Massively increasing lifetime of the network. <br> - Build a more stable routing environment. |
| LEACH-B | - Balance the network by considering the node's residual energy. <br> - Number of CHs is constant and near-optimal per round. | Dynamic | Yes | Single-hop | - Balance the system energy consumption. <br> - Increase network lifetime. |
| LEACH-R | - Based on residual energy and distance to sink, R nodes are chosen to become relay nodes between the sink and the other CHs. | Dynamic | Yes | Three-hops | - Save around $20 \%$ energy of the WSN. |
| AEEC | - Balance energy usage by assigning nodes having more residual energy with more chances to be selected as CHs. <br> - Use elector nodes, responsible for collecting energy information of the nearest sensor nodes and selecting the CHs. | Dynamic | Yes | Single-hop | - Balance energy consumption in the network. <br> - Increase network lifetime. |
| Energy-LEACH | - Consider the residual energy in the sensor nodes to balance the network load. <br> - Change the round time, depending on the optimal cluster size. | Dynamic | Yes | Single-hop | - Increase network lifetime at least by $40 \%$. |
| I-LEACH | - Residual energy is used to select the CH. <br> - Deployed for sensor nodes with different initial energies. <br> - Coordinates are used to form clusters so that there remains a CH close to every sensor node. | Dynamic | Yes | Single-hop | - Increase network lifetime. <br> - $15 \%$ more energy efficiency. |

Table 1 (Continued)

| Protocol Name | Extensions | Cluster formation | Energy Efficiency | Connectivity | Performance improvements |
| :---: | :---: | :---: | :---: | :---: | :---: |
| MG-LEACH | - Minimize redundancy when WSN contains plenty of redundant information. <br> - Redundant information describing the same event are discarded by CHs. Location process is used for node coordination. | Dynamic | Yes | Single-hop | - Increase network lifetime. |
| Improved Multi-Hop Leach | - Use both inter-cluster and intra-cluster communication. <br> - Deploy CH and vice CH, which replaces its CH when needed. | Dynamic | Yes | Multi-hop | - Balance the system energy consumption. <br> - Increase network lifetime. <br> - Maintain connectivity and reduce loss rate. |
| EAERP | - Use the formulation of the fitness function to find clustered routes that minimize the overall energy dissipated by the network. <br> - Over rounds, the individual energies of the CHs are expended, but in a spaced interval fashion. | Dynamic | Yes | Single-hop | - Derive clustered routes with better tradeoff between network stability and network lifetime. <br> - Guarantee a well-distributed energy consumption. |

cluster formation, energy efficiency, type of the connectivity, and the desired objectives.

## 3. Proposed LEACH-based clustering algorithm

After intensive study of the LEACH protocol and its weaknesses, we propose a new LEACH-based clustering algorithm called enhanced multi-hop LEACH (EM-LEACH), which improves the network efficiency, particularly in terms of energy distribution, leading to increased network lifetime and an increased amount of received data. First, this algorithm is based on new rules for CH selection and round time computing that use the residual energy of the network. Second, EM-LEACH integrates the multi-hop communication model by using a leveling phase and a generic multi-hop routing process.

### 3.1. Clustering: new approach for CH selection

Each node in the network randomly decides whether to become a CH for the current round. This decision is made by the node choosing a random real number between 0 and 1 . If the chosen number is less than a threshold, $T(n)$, the node becomes a cluster-head for the current round, as defined in basic LEACH. Moreover, the residual energy constitutes another important factor for selecting the suitable cluster-head. This is the reason Eq. (2) includes a second term to describe the impact of the remaining energy ratio in each sensor on the CH selection process.
$T(n)=\left\{\begin{array}{l}\frac{1}{2} *\left[\beta *\left(\frac{\rho}{1-\rho *\left(r * \bmod \frac{1}{\rho}\right)}\right)+(1-\beta) *\left(\frac{E_{\text {residual }}}{E_{\text {initial }}}\right)\right], \\ 0, \\ \text { if } n \varepsilon G \\ \text { otherwise }\end{array}\right.$
Where:

- $\beta=\mathrm{E}_{\text {residual }} / \mathrm{E}_{\text {initial }} \cdot \mathrm{E}_{\text {residual }}$ and $\mathrm{E}_{\text {initial }}$ are the residual and initial energies of node $n$, respectively.
- $\rho$ is the desired percentage of $\mathrm{CHs}, r$ is the current round, and $G$ is the set of nodes that have not been cluster-heads in the last $1 / \rho$ rounds.
- $\beta$ (resp $1-\beta$ ) is the weight attributed to the percentage $\rho$ (resp. residual energy $\mathrm{E}_{\text {residual }}$ ).

By default, $\beta$ is reset to 1 , because there is no need to consider the energy at the first round while all nodes have full batteries. Thus, basic LEACH is applied only during this round. For the following rounds, the round number, $r$, increases, $\beta$ decreases, and $1-\beta$ increases, which balances the weight between the percentage and residual energy needed to select cluster-heads.

For the first criteria, Eq. (2) is proposed by the sum of two terms, including the percentage and the remaining energy ratio with different coefficients, $\beta$ and ( $1-\beta$ ), respectively. During the first round, the default $\beta$ is equal to 1 , resulting in CHs selected based only on the first term (percentage), because the sensor's batteries are fully charged. During this round, our proposal behaves similarly to LEACH. Subsequently, $\beta$ deceases and both terms contribute to select the suitable CHs in the network. When $\beta$ decreases, ( $1-\beta$ ) increases, making the percentage and the remaining energy ratio inversely proportional values for CH selection. After several rounds, the residual energy ratio, included in the second term by $\mathrm{E}_{\text {residual }} / \mathrm{E}_{\text {initial }}$, becomes the most important factor used for CH selection.

As second criteria, $\beta$ should be dynamically adjusted from 1 to 0 during the network lifetime to balance the decision for CH selection between the two terms. During the network lifetime, the residual energy decreases From $\mathrm{E}_{\text {initial }}$ to 0 , so that $\mathrm{E}_{\text {residual }} / \mathrm{E}_{\text {initial }}$ decreases from 1 to 0 . Therefore, $\beta$ is assigned to $\mathrm{E}_{\text {residual }} / \mathrm{E}_{\text {initial }}$ as a parameter inspired from the network itself. $\beta$ is function of $E_{\text {residual }}$ in each node.

Our model uses an additional operator allowing it to include the energy in the CH selection process only when its level decreases. However [15], introduced the remaining energy rate from the beginning of the network operation, while the batteries are fully charged. Moreover, computing $\mathrm{k}_{\text {opt }}$ each round may introduce extra overhead, resulting in additional energy consumption. In the same context [17], used a non-linear cluster-head expected frequency appraisal function, $\Psi$ ( $\mathrm{K}_{\text {i_expect }}$ ), for cluster-head selection. Thus, its implementation is more complex and must process overhead.

In the setup phase, two steps follow the CH selection: cluster formation and schedule creation. During cluster formation, all cluster-heads broadcast advertise packets with maximum transmission power using CSMA. Each node chooses the closest cluster-head, based on the RSS of the advertisement packets, and they send a notification to join a target cluster. The CH creates a TDMA-based transmission schedule for each member node in the cluster. In the steady-state phase, each member node transmits data during its own timeslot and reduces energy consumption by entering sleep mode during the remaining timeslots. The CH aggregates the data received from nodes inside the cluster and sends it to the sink.

### 3.2. Data aggregation and round time computing

During the data transmission phase, the CH consumes more energy because (a) it supports all traffic delivered from sensors and (b) it wakes up the most times to manage the communication with the regular nodes and the other cluster-heads or sink.

Both Refs $[15,17]$. used a fixed round time during the entire network operation. However, our model (EM-LEACH) proposes a variable round time, because the remaining energy decreases at every sensor node (Eq. (3)). Therefore, to prevent depleting the CH remaining energies and losing more data, EM-LEACH adapts the round time according to the remaining energy in the entire network without extra overhead. The remaining energy level is usually included by the sensor node in the data packets and updated at the sink node without using separate packets. Thus, an adaptive round time, based on the total residual energy, leads to fair distribution of energy consumption among all nodes.

Eq. (3) leads to an energy-round length adequacy for fair consumption among the different rounds. We used default values for the initial round length and the energy rate of all nodes. At the beginning, the initial round time is fixed to $150 \%$ of the LEACH round time. Then, it decreases progressively to finally reach $50 \%$ of the LEACH round time as the lowest value. Many experiments have been done using Eq. (3) with various values of $\alpha$, where the best results are obtained with $\alpha=1.5$. Eq. (3) is a hyperbolic function, and the value of $\alpha$ has been estimated to dynamically decrease the round time similarly to the residual energy.
Round Length $=$ Initial Round Length ${ }^{*}\left(1-\frac{1-\text { Energy rate }}{\alpha+\text { Energy rate }}\right)$

### 3.3. Leveling phase

All nodes in LEACH can reach the sink with a high-power transmission, which leads to a significant loss of energy. These losses can be mitigated by introducing multi-level clusters to support multihop routing. In this study, each node gets a level number during setup. The level number is included in the first setup packet and is sent from the sink of level 0 . The setup packet propagates across the network, and the level number is incremented from lower levels for nodes neighboring the sink toward the higher levels at the other network edges. In this study, the setup packet transmission power is adjusted to -5 dBm (Table 2). Therefore, multiple hops must be recorded to cover the entire network area. Additionally, the maximum number of levels depends of the network topology, which is random.

The leveling process allows the network to be organized as a tree-based routing structure to make multi-hop packet forwarding easy during the data transmission phase. In the leveling phase, we consider the conservation of energy as much as possible by sending only one setup packet. The number of levels depends on the transmission power of the setup packet. If the transmission power is high, the node can send data for longer distances, which make the

Table 2
Simulation Parameters.

| Number of sensor nodes | 100 |
| :--- | :--- |
| Deployment area | $70 \times 70 \mathrm{~m}$ |
| Location of the sink node | $(0,0)$ or center |
| Deployment of the sensor nodes | random |
| Packet rate | 100 packets $/ \mathrm{s}$ |
| Packet size | 9 Bytes |
| Radio | CC2420 |
| Initial energy (sensor nodes) | $5 \mathrm{~J}, 10 \mathrm{~J}$ |
| Percentage | 0.05 |
| Setup packet transmission power | -5 dBm |



Fig. 1. Flowchart of leveling phase.
number of levels small, and vice versa. Fig. 1 shows the flowchart describing the leveling phase.

### 3.4. Multi-hop routing phase

In our model, we use a multi-hop routing mechanism from lower levels toward higher levels. Data move from nodes to their corresponding CH and then consecutively to lower level CHs until reaching the CH in level 1 which forwards data to the sink node.

In the setup phase, after electing CHs in each level using Eq. (2), all cluster-heads broadcast advertise packets with maximum transmission power using CSMA. In the cluster formation step, each node chooses the closest cluster-head in the same level, based on the RSSI of the advertisement packets and sends a notification to join a target cluster. However, when the node does not receive the CH advertisement packets from the same level, it checks to receive a CH advertisement from any other level ( $i$ ). In this case, the node changes its current level to level ( $i$ ). Moreover, when no CH advertisement is received, the node aggregates data directly to the sink. During the cluster formation step, the multi-hop organization step occurs where each CH chooses its closest CHs at lower levels, based on the RSS of the CH advertisement packets. It then sends a notification to join this CH . If the CH does not receive any CH advertisement from lower levels, it sends aggregations directly to the sink. This ensures the network will be dynamically aware in the event of node failures.


Fig. 2. Multi-hop routing (a) sink in the corner (b) sink in the center.


Fig. 3. Flowchart of clusters formation in EM-LEACH.

The cluster formation step and multi-hop organization happens synchronously, almost simultaneously to save time and energy. Clustering, leveling, and multi-hop routing processes are introduced in our approach to limit the apparition of partitions. These processes should be re-executed periodically to re-organize the WSN, in terms of function and level of nodes and number and dimension of groups. LEACH is susceptible to the apparition of partitions, because a degraded transmit power is unable to radiate over a long distance. However, with the multi-hop aspect, partitions are not expected.

In the steady-state phase, each cluster-head creates a TDMA schedule for all nodes joined the cluster and the CHs at the higherlevel. Each member node transmits data during its own timeslot and reduces the energy consumption by entering sleep mode during the remaining timeslots. The CH aggregates the data received from various nodes inside the cluster and sends it to the sink or to the higher-level CH . At the end of each round, the sink reads the residual energy in each node in the network and finds the energy rate to use it for round time computing, as given in Eq. (3).

Thus, multi-hop routing reduces the load and duplicated packets in the network, and improves the energy efficiency of the WSN. Fig. 2 explains multi-hop routing, where the sink is in the corner, (a), and in the middle of the network area, (b). Fig. 3 shows the flowchart of cluster formation in EM-LEACH.

### 3.5. EM-LEACH processes interworking

Fig. 4 shows the EM-LEACH flowchart summarizing the different processes operating in each round. The EM-LEACH processes operate in the following sequence.

- Leveling phase
- Setup phase
- CH election
- Cluster formation
- Multi-hop organization
- Steady-state phase
- Schedule creation
- Data transmission
- Round time calculation

The leveling and setup phases require the organization of the network as a tree-based routing structure, where a level number is assigned to each node to make multi-hop packet forwarding easy during the data transmission phase. The cluster formation step and multi-hop organization happens synchronously, almost simultaneously to save time and energy. CHs aggregate data received from both nodes of their clusters and from higher-level CHs to forward them to lower CHs. At the end of each round, the next round duration is calculated, based on the residual energy of the entire network.

## 4. Simulation environment and results

Castalia is a WSN simulator, generally for low-power wireless embedded devices. It is based on the OMNeT++ platform and can be used to test distributed algorithms and/or protocols in realistic wireless channel and radio models. It displays realistic node behavior, especially relating to radio access [26].

### 4.1. Network model

There are many possible models for WSNs. For our algorithms, we make the same assumptions as LEACH about the network model, as follows.

- The network is static and nodes are distributed randomly.
- A sensor contain two kinds of nodes: sink nodes (no energy restriction) and common nodes (with energy restriction).
- There exists only one sink node, fixed and localized far from the sensors at one of two positions: at the corner $(x=0, y=0)$ or in the center.
- The network is homogeneous and all common nodes have equal initial energy at the time of deployment.
- The energy of sensor nodes cannot be recharged after deployment.
- All nodes can transmit with enough power to reach the sink if needed.


### 4.2. Simulation setup and parameters

Castalia is designed to model a wide range of physical sensor networks of varying node densities. Castalia has 11 distinct random number streams that affect different parts of the simulation. It allows us to run the simulations with more than one set of random seeds. Three repetitions of the simulation have been used to successfully extract every performance metric. However, results do not change much after running just one simulation. Statistically, the average is used to give the results a certain confidence level.


Fig. 4. EM-LEACH global flowchart.

For simulation purposes, we created a static network of 100 sensors scattered in a $70 \mathrm{~m} \times 70 \mathrm{~m}$ area. The sensor nodes were randomly deployed like several real WSN setups, and the sink was placed at location ( $x=0, y=0$ ). In the simulation, some results were well-extracted with the sink node at the center, reflecting some environmental applications. The radio module used in this work is CC2420, which is a real single-chip operating at a $2.4-\mathrm{GHz}$ frequency band, compliant with IEEE 802.15.4 RF. The transceiver is designed for low-power and low-voltage wireless applications. CC2420 is used in the TelosB platform.

The size of the data packets is fixed to 9 bytes. The desired percentage $p$ of CHs is fixed to 0.05 as deployed in LEACH [6]. In terms of energy, we assume that nodes begin with an equal energy level and an unlimited amount of data to send to the sink. Once a node runs out of energy, it is considered dead, and can no longer transmit or receive. We simulated both LEACH, MR-LEACH and EM-LEACH using two different initial energies ( 5 J and 10 J ) to allow study and analysis of the energy effect. The simulation parameters are listed in Table 2.

### 4.3. Performance measures

The performance metrics are organized into three classes: lifetime, reliability, and energy efficiency.

Lifetime

- Lifetime: the main metric evaluating the network performance measures network lifetime. The network lifetime is measured as the time interval from the start of network operations until the LND.
- Stability period: this period is defined as the time interval from the beginning of network operations until the FND.

Reliability

- Received data packets: the total amount of data received at the sink. It represents an important metric to measure the reliability performed by our algorithm.
- Network throughput: is the rate of successful packet delivery over a communication channel per period.


## Energy efficiency

- Energy: the distribution of consumed (or residual) energy may reflect the effectiveness of the algorithms. In other terms, the energy is fairly distributed in the network when the gap between residual energies in the sensors is low. More fairness in energy distribution positively impacts network lifetime.
- Energy dissipated: Total energy dissipation by the sensor nodes used for data processing and communications per period. This metric shows the scale of energy consumption in the network.
- Average energy consumed: is the average consumed energy in a specific cluster per round time for both CH and member nodes.


Fig. 5. FND and LND. Initial energy: 5 J in (a) \& 10 J in (b).


Fig. 6. Total number of received data packets at the sink. Initial energy: 5J in (a) \& 10J in (b).


Fig. 7. Received data vs number of alive nodes. Initial energy: 5 J in (a) \& 10 J in (b).

The lower the gap between clusters' average consumed energy in each round, the more balance of distributed energy in the network and more prolonged the lifetime.

### 4.4. Performance evaluation

Using Castalia, the simulation was done under the same scenario, using both initial energy levels 5 J and 10 J . The performance


Fig. 8. Received data packets vs energy consumed. Initial energy: 5 J in (a) \& 10 J in (b).


Fig. 9. Network throughput. Initial energy: 5 J in (a) \& 10 J in (b).


Fig. 10. Total amount of energy dissipated vs Time. Initial energy: 5 J in (a) \& 10 J in (b).
evaluation considers LEACH, MR-LEACH and EM-LEACH for comparison in terms of network lifetime, reliability, and energy efficiency.

### 4.4.1. Network lifetime

Network lifetime is measured as the time interval from the start of network operations until the LND. Fig. 5 illustrates the performance of the EM-LEACH algorithm, compared to LEACH and


Fig. 11. Average energy level consumed by clusters per round.

MR-LEACH in terms of network lifetime. FND for EM-LEACH and MR-LEACH occurs before LEACH, because of the initialization step. However, EM-LEACH keeps certain number of nodes alive longer compared to LEACH. The simulation results prove the improvement of EM-LEACH performance with around $16 \%$ to $25 \%$ extra lifetime, compared to LEACH. It shows similar performance as MR-LEACH. These figures consider two different initial sensor energies: 5 J in (a) and 10 J in (b).

### 4.4.2. Network reliability

Fig. 6 shows the total number of received data packets at the sink for LEACH, MR-LEACH and EM-LEACH algorithms with two different initial energy levels: 5 J in (a) and 10J in (b). With 5-J initial energy, the number of received data packets was $245 \%$ and $143 \%$
better for EM-LEACH compared to LEACH and MR-LEACH, respectively. This result was repeated with 10-J initial energy, where EM-LEACH performed up to $200 \%$ and $126 \%$ better than LEACH and MR-LEACH, respectively. This is because of two contributions. First, the round time adequacy with the remaining energy allows nodes to deliver packets to their neighbors according to their own residual energies. Second, multi-hop communication is characterized by low range, interference, and collision aspects, which increases the probability of packet delivery.

Moreover, (1) the leveling phase and (2) the various scenarios included in EM-LEACH to solve all communication issues that may occur between cluster-heads (multi-hop, single hop and restriction of communication direction) constitute the major contributions that successfully increase packet delivery (see Section 3.4). How-

Table 3
Details of data packets delivered to the sink node.

| Number of packets | LEACH |  | MR-LEACH |  | EM-LEACH |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 5 J | 10J | 5 J | 10J | 5 J | 10J |
| Received with no interference | 1,162 | 2,076 | 1,998 | 3,571 | 2,852 | 4,541 |
| Received despite interference | 16 | 26 | 18 | 28 | 19 | 30 |
| Total received Packets | 1,178 | 2,102 | 2,016 | 3,599 | 2,871 | 4,571 |

ever, with MR-LEACH, no packet is received after 260 s in (a) and 413 s in (b) since alive nodes are becoming isolated to each other.

Fig. 7 shows the number of data packets delivered to the sink node per the number of alive nodes for LEACH, MR-LEACH and EMLEACH algorithms. The result is more significant for EM-LEACH compared to both LEACH and MR-LEACH. Moreover, EM-LEACH performed better for packet delivery (i.e. network reliability) for both initial energies of 5 J and 10 J . Under the same scenario, the maximum gap of packet delivery between LEACH, MR-LEACH and EM-LEACH was given at the end of the network life time (i.e. all nodes died) (Fig. 7(a) \& (b)). During the last stage of the network lifetime, alive nodes become isolated, disconnectivity of clusters appears and consequently the number of delivered packets is slightly increasing. This aspect is more significant with LEACH and MR-LEACH. Table 3 provides precise details about the total number of data packets supported by these algorithms and successfully delivered to the sink node.

Fig. 8 estimates network reliability per the energy consumption for all three algorithms (LEACH, MR-LEACH and EM-LEACH) using two different initial energies: 5 J in (a) and 10 J in (b). We can infer that energy consumption for EM-LEACH and MR-LEACH is less than LEACH, because the transmit power in each node (member, CH ) is dynamically adjusted. Additionally, the leveling process introduced by EM-LEACH only allows data to propagate in a decreasing way toward the sink node, constituting a second key element for energy saving. This process prevents packets from propagating in other ways, so that energy is conserved. Therefore, the same amount of energy allows delivering more packets with EM-LEACH compared to LEACH and MR-LEACH.

Fig. 9 measures the throughput of data packets in the whole network for LEACH, MR-LEACH, and EM-LEACH using two different initial energies: 5 J in (a) and 10 J in (b). The throughput performed by EM-LEACH presents two aspects of variations: a fast-increasing variation followed by a slow decreasing variation. First, the fastincreasing variation is stimulated by the multi-hop aspect that increases the probability of successful packet delivery. Second, the slow decreasing variation is caused by the degradation of energy in the network and the death of some nodes. In other terms, packet delivery is low and therefore the throughput is decreasing. With LEACH, the throughput is weak because of the waste of energy and collisions. Moreover, a node may be elected to CH without considering its remaining energy. During this round, the CH may be unable to reach the sink node because of its degraded transmit power. Therefore, energy is consumed for generating packets that may not reach the sink node. Alternatively, MR-LEACH provides medium performance, based on its own multi-hop feature.

### 4.4.3. Energy efficiency

Fig. 10 shows the amount of dissipated energies while using LEACH, MR-LEACH, and EM-LEACH with two different initial energy levels: 5 J in (a) and 10 J in (b). The dissipated energy is measured as the total energy consumed by the sensor nodes per period. Fig. 10 shows that EM-LEACH consumes energy slightly higher than LEACH and MR-LEACH within the network lifetime. This result is caused by the extra data packets supported and delivered by EM-LEACH, compared to the other algorithms as outlined in Figs. 7 and 8. To
confirm this result, the simulation was performed with different initial energies and various sink node locations.

Fig. 11 shows the average energy level consumed by each cluster per round

## 5. Conclusion

In this paper, we proposed a new extended LEACH-based clustering algorithm to enhance WSN performance in terms of reliability, energy efficiency, and lifetime. First, our algorithm, EMLEACH, supports new rules for cluster-head selection and round time computing based on the remaining energy. Second, EM-LEACH improves the communication model from single-hop to multi-hop between CHs and sink node using two operating processes: leveling and generic multi-hop routing.

The Castalia simulator was used to evaluate the performance of the proposed algorithm, EM-LEACH, compared to LEACH and MR-LEACH. The performance evaluation included different aspects related to network reliability, energy efficiency, and lifetime. The simulation results proved that the performance improvement of EM-LEACH algorithm, in terms of packet delivery, is extremely good compared to LEACH and MR-LEACH. Additionally, EM-LEACH provided around $16 \%-25 \%$ extra network lifetime compared to LEACH and presented results similar to MR-LEACH.

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[^0]:    * Corresponding author.

    E-mail addresses: Saalsodairi@pnu.edu.sa (S. Al-Sodairi), rouni@ksu.edu.sa (R. Ouni).

