An Adaptive LEACH-based Clustering Algorithm for Wireless Sensor Networks

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***Abstract*— LEACH is the most popular clastering algorithm in Wireless Sensor Networks (WSNs). However, it has two main drawbacks, including random selection of cluster heads, and direct communication of cluster heads with the sink. This paper aims to introduce a new centralized cluster-based routing protocol named LEACH-AEC (LEACH with Adaptive Energy Consumption), which guarantees to generate balanced clusters over the network. In LEACH-AEC, more information from the current state of nodes (including the residual energy of nodes, the distance from sink, and the distances between cluster heads) are considered to select the optimal cluster heads. Also, the multi-hop routing extension via A-Star algorithm is utilized in LEACH-AEC to cope with routing in large topological WSN areas. In contrast to the previous cluster-based protocols, the main advantage of LEACH-AEC is to prolong the network lifetime, based on the application specifications. Simulation results show that the proposed routing protocol plays an effective role in reducing energy consumption, provides a balanced consumption of energy and increases the lifetime of the network.**

***Index Terms*—** Clustering, Data Transmission, Energy Consumption, Routing Protocol, Wireless Sensor Networks.

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a collection of compact-size computational nodes capable of detecting local environmental conditions, and forwards such information to a central sink for appropriate processing. Since sensor nodes are battery-powered and may be used in dangerous or inaccessible environments, it is difficult to recharge the energy supplies. Therefore, energy limitation is the main problem in WSNs, and efficient techniques are highly required to prolong the network lifetime. WSNs provide unprecedented opportunities in several domains including military, agriculture, structural monitoring, industrial control, health monitoring, and etc. [1].

Unlike wired systems, the installation cost in WSNs is set to minimum. In addition to reduce the deployment cost, a WSN has the ability to adapt with changes in the network environment [2].

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The environment can be physical world, a biological system, or an information technology framework. A wireless sensor node consists of four major parts: sensor unit, processing unit, energy supply unit, and transceiver. The sensing circuitry transforms the sensed data into an electric signal. Each node then sends the sensed data via radio transmitter to the central sink, either directly or through intermediate nodes [3].

In WSNs, a routing protocol is required when a node cannot send its data packet directly to the sink [4]. In recent years, many routing protocols have been proposed to achieve the energy efficiency in WSNs. Generally, routing techniques in WSNs can be classified into three categories: flat, location-based, and hierarchical protocols [5]. In general, cluster-based routing protocols segment a network into distinguished non-overlapping clusters, each contains a Cluster Head (CH). The regular (non-CH) nodes transmit their data to corresponding CHs, where the collected data packets can be aggregated and transmitted to the sink. Selection of the appropriate CHs can significantly reduce the overall energy consumption and prolong the network lifetime [5]. Generally, the routing procedure in cluster-based approaches consists of two phases: setup phase and steady state phase. In the setup phase, CHs are selected among all nodes within the network, and then, clusters are formed by simply assigning each node to the closest CH. In the steady state phase, the regular nodes transmit the sensed data packets to the corresponding CHs, and then, the CHs send the collected data packets to the sink [6].

LEACH (Low Energy Adaptive Clustering Hierarchy) [7] is the most popular and attractive hierarchical protocol which is widely accepted for its simplicity. LEACH tries to balance the energy consumption by rotating the role of CH among all nodes. This protocol tries to reduce the energy consumption by clustering sensor nodes into distinguished non-overlapping clusters, putting nodes to sleep in various time intervals, and aggregation of the collected data in CHs. However, it has two main drawbacks, including the random selection of CHs, and the direct communication of CHs to the sink, without any intermediate node.

As mentioned above, the current state of the sensor nodes (e.g., the residual energy, their position, the distance from the sink, etc.) is not considered in the LEACH protocol. In recent years, many extensions of LEACH have been proposed, including the energy-aware sliding windows protocol [8], the centralized energy-aware LEACH-EP protocol [9], the distance-aware protocol using the minimum and maximum allowable distance from the sink [10], the distance-aware LEACH-DT protocol [11], the multi-hop Dijkstra's protocol [12], and etc. LEACH-EP is an energy-aware centralized protocol, in such a way that the CH-selection procedure is utilized in a processor located in the sink. In LEACH-EP, those nodes which their residual energy is greater than a predetermined threshold can be selected as CHs. The more residual energy a node has the more probability for that node to be selected as a CH [9]. Also, in LEACH-DT, the distance from the sink is used to balance the energy consumption of all nodes. The node with large distance from the sink has less probability to be CH, as compared with those nodes within the vicinity of the sink [11].

Distributed clustering protocols are more appreciated, because they have a stochastic self-election mechanism. On the other hand, in the centralized protocols, the residual energy of sensor nodes is considered to select the cluster heads in the centralized processor. Although the centralized solutions prolong the network lifetime better than the distributed ones, they increase overhead and delay to transmit data packets. Typically there are three kinds of overhead in the centralized protocols: 1) each node should send extra information (e.g., the residual energy) along with the sensed data to the sink, 2) the calculations for the cluster head selection in the sink have some computational complexity and 3) sink should send messages to all selected nodes to inform them that they are the current cluster heads.

Recently, evolutionary algorithms [4, 5, 13, 14] and fuzzy logic [15 - 18] also have begun to attract attention from researchers to develop hierarchical cluster-based protocols in WSNs. The main goal of the evolutionary-based clustering protocols is to dynamically cluster the sensor nodes in setup phase in such a way that the energy consumption is minimized. For N sensor nodes, there are totally (2^N-1) different solutions, where in every solution each node can be either selected as a cluster head or not [4]. Generally, the fuzzy-based approaches aim to select the appropriate CHs in the each round via fuzzy inference systems. These techniques are distinguished by how the CHs would be selected via fuzzy logic.

In this paper, a new centralized cluster-based routing protocol named LEACH-AEC (LEACH with Adaptive Energy Consumption) is introduced, that takes into account more information from the current state of sensor nodes (including the residual energy of nodes, the distance from sink, and the distances between cluster heads) to select the optimal cluster heads. Considering the distance between the cluster heads leads to generate balanced clusters over the network. Also, in LEACH-AEC, the multi-hop routing extension via A-Star algorithm is utilized, in order to cope with routing in large topological WSN areas. In this way, those cluster heads which are far from the sink, can communicate hop-by-hop with the sink via intermediate cluster heads, in order to reduce the energy consumption of initial cluster heads. In contrast to the previous cluster-based protocols, the main advantage of LEACH-AEC is to prolong the network lifetime, based on the application specifications.

The rest of this paper is organized as follows: In Section II, some related cluster-based routing protocols are discussed. Section III introduces the LEACH-AEC routing protocol in details. In Section IV, the communication model used for simulation in WSNs is addressed and also present the simulation results. Finally, some conclusion remarks with possible future directions can be seen in Section V.

II. RELATED WORKS

In this Section, we discuss three related cluster-based routing protocols, including LEACH, LEACH-EP, and LEACH-DT, in details. These protocols are the most similar approaches to our LEACH-AEC protocol. On the other hand, our routing protocol is inspired and is based on these three algorithms. LEACH [7] is a probability-based CH-selection protocol which uses stochastic self-election. The operation of LEACH protocol in the each round can be separated into setup phase and steady phase. In the setup phase, each sensor node chooses a random number between 0 and 1. It becomes a CH for the current round, if its random number is less than *T*(*n*), which is calculated as follows:

$$T(n) = \begin{cases} \frac{P}{1-P\left(r \bmod \frac{1}{P}\right)} & ; n \in G \\ 0 & ; otherwise \end{cases} \tag{1}$$

where *P* is the desired probability for becoming CH, *r* is the current round, and *G* is the set of sensor nodes that have not been selected as CH in the last 1/*P* rounds. The optimal desired probability for becoming CHs (*P*) is 5% of all sensor nodes [7]. The main objective of LEACH is its rotation mechanism and its data aggregation strategy. However, it has some drawbacks as follows: 1) the distance of nodes from the sink is not considered. The nodes which are far from the sink have the same probability for becoming CH, as compared with those nodes in the vicinity of the sink. Therefore, the nodes which are far from the sink would be rapidly dead. 2) The residual energy of nodes is not taken into account. On the other hand, if the node with lower residual energy decides to be a CH, it will be rapidly dead. It can highly reduce the network lifetime. 3) It is single-hop, in such a way that CHs are communicated directly with the sink. Therefore, those CHs which are far from the sink should send the gathered data directly to the sink, without utilization of the intermediate CHs.

LEACH-DT (LEACH with Distance-based Threshold) [11] is a distance-aware LEACH-based algorithm, which considers different probabilities for becoming CH in sensor nodes based on their distance from the sink. On the other hand, the lower distance from the sink, the more probability to be selected as a CH. Like the original LEACH, it is a distributed algorithm with stochastic self-election mechanism. The similar threshold is used, as seen in Eq. (1). However, unlike LEACH, the probability *P* is not a constant parameter, and is related with the reverse of the distance from the sink. The probability of node *n* can be formulated as follows:

$$P(n) = \frac{k \times \xi(n)}{\sum_{i=1}^{N} \xi(i)} \tag{2}$$

where *P*(*n*) is the probability of node n, k is the desired number of CHs, and $\xi(n) = 1/(\bar{E}_{CH} \times d(n) - \bar{E}_{Reg})$, in which, *d*(*n*) is the distance of node *n* from the sink, $\bar{E}_{CH}$ is the average energy of CHs in the previous round, and $\bar{E}_{Reg}$ is the average energy of the regular nodes in the previous round. The energy consumption in LEACH-DT is more balance than that of in LEACH protocol. Simulation results show that LEACH-DT outperforms the original LEACH with improved network lifetime over 10% in the first node dies criterion [11].

LEACH-EP [9] improves the cluster-head-electing threshold of LEACH, and inherits its advantages like the mechanism of rounds, spontaneously creating clusters, and so on. In LEACH-EP protocol, the node with more residual energy has more opportunity to be served as CH. Due to obtaining the number of surviving nodes and the average remaining energy of cluster-heads in last round, this algorithm differs from LEACH in implementation strategy. The energy-aware threshold in LEACH-EP can be calculated as follows:

$$T(n) = \begin{cases} \frac{P \times E(n)}{E_{CH}} & ;\ E(n) \geq 0.5 \times E_{CH} \\ 0 & ;\ E(n) < 0.5 \times E_{CH} \end{cases} \quad (3)$$

Where, P is the desired percentage of nodes to be selected as CHs, $E(n)$ is the residual energy of node n, and E_{CH} is the average residual energy of the CHs in the previous round. Authors in [9] show that LEACH-EP improves the network lifetime over 33% in contrast to the original LEACH protocol.

III. PROPOSED PROTOCOL

A. Overall operation of LEACH-AEC

Like the original LEACH, the operation of the proposed LEACH-AEC routing protocol in the every round can be separated into two main phases: the setup phase, and the steady state phase. The setup phase includes the CH-selection and cluster forming steps. Also, the steady state phase includes the data transmission step. It is notable that the CH-selection procedure in LEACH-AEC is centralized, in such a way that the decision for selection of CHs is done sequentially in all sensor nodes, node-by-node until all nodes are evaluated.

The CH-selection procedure is utilized in a processor located in the sink. In this way, an adaptive threshold $T_{AEC}(i)$ is determined for the each node i, which is calculated based on the residual energy of node i, the distance of node i from the sink, and the minimum distance of node i from the nearest CH selected in the current round, so far. Then, the node i choose a random number between 0 and 1. It becomes a CH, if its random number is less than $T_{AEC}(i)$. Otherwise, the node i is considered as a regular node. The mentioned procedure is done for all nodes sequentially node-by-node.

After selection of the appropriate CHs in the every round, the sink broadcasts a message to all selected CHs to inform them that they are the current CHs. Then, each CH broadcasts advertise messages to all nodes within the network. Each regular node selects the nearest CH based on the received signal strengths from CHS. Then, it sends a request to join to the corresponding CH to inform the CH that it is a member of that cluster. After forming the clusters, each CH creates a Time Division Multiple Access (TDMA) schedule based on the member count, and tells each member node the time slot that it can transmit its data packet.

Once all clusters are formed and the TDMA scheduling is created, the data transmission phase could begin. During the steady phase, each regular node transmits its collected data packet to the corresponding CH within the determined time slot in TDMA scheduling. After receiving all data packets in CH from all member nodes, the CH can aggregate the gathered data packets and sends them to the sink. Since in the large-scale WSNs there is some CHs which are located very far from the sink, they would rapidly be dead, if they communicate directly with the sink. Therefore, the CH which its distance from the sink is greater than a specified threshold value, should communicate via intermediate CHs using multi-hop extension in LEACH-AEC using A-Star algorithm.

B. Cluster-head selection procedure in LEACH-AEC

Unlike original LEACH protocol, the threshold T in the proposed LEACH-AEC protocol is not a constant parameter for all nodes, and is adaptively calculated based on the residual energy of nodes and their location in the network. In the proposed methodology, the nodes with more residual energy and lower distance from the sink have more chance to be selected as CHs. Also, the distances between CHs are considered for CH-selection procedure in order to have a good distribution of CHs over the network. In LEACH-AEC, the hybrid adaptive weighted threshold for node i, $T_{AEC}(i)$, can be calculated as follows:

$$T_{AEC}(i) = \begin{cases} w_1 \times P_1(i) + w_2 \times P_2(i) + w_3 \times P_3(i) & ;\ P_1(i) > 0 \ and \ P_3(i) > 0 \\ 0 & ;\ otherwise \end{cases} \tag{4}$$

Where w_1, w_2, and w_3 are three weighting parameters which adjust the relative important of the three terms within Eq. (4). These weights should be determined in such a way that the sum of them be equal to one: $w_1 + w_2 + w_3 = 1$. It should be done in order to normalize the average probability of nodes into P, similar to the original LEACH. The P_1, P_2, and P_3 can be formulated as follows:

$$P_1(i) = \begin{cases} P \times \frac{E(i)^{\alpha}}{\frac{1}{N}\sum_{n=1}^{N} E(n)^{\alpha}} & ;\ E(i) \geq t \times \frac{1}{N}\sum_{n=1}^{N} E(n) \\ 0 & ;\ otherwise \end{cases} \tag{5}$$

$$P_2(i) = P \times \frac{\frac{1}{d(i)}}{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{1}{d(n)}\right)} \tag{6}$$

$$P_3(i) = \begin{cases} P & ;\ round = 1 \quad or \quad SH = 0 \\ P \times \frac{DH(i)}{DH_{pre}} & ;\ round > 1 \ \ and \ \ SH > 0 \ \ and \ \ DH(i) > d_{min} \\ 0 & ;\ round > 1 \ \ and \ \ SH > 0 \ \ and \ \ DH(i) < d_{min} \end{cases} \tag{7}$$

In the above equations, the indices and parameters can be defined as follows:

N	Total number of alive sensor nodes in the network in the current round
M	Length of the topological workspace area (meter)
SH	Number of cluster heads selected in the current round, so far
P	Desired percentage of clusters
n	Node index, $n = 1,2, \dots, N$
i	Node index, $i = 1,2, \dots, N$
$E(i)$	Residual energy of node *i* (joule)
α	Power ratio of energy
$d(i)$	Distance of node *i* from the sink (meter)
d_{min}	Minimum allowable distance between two cluster heads (meter)
$DH(i)$	Minimum distance of node *i* from the selected cluster heads in the current round, so far
DH_{pre}	Mean of all distances between cluster heads in the previous round
$T_{AEC}(i)$	Adaptive hybrid threshold of node *i* to be selected as cluster head
$P_1(i)$	First term in $T_{AEC}(i)$: a function of the residual energy of node *i*
$P_2(i)$	Second term in $T_{AEC}(i)$: a function of the distance of node *i* from the sink
$P_3(i)$	Third term in $T_{AEC}(i)$: a function of the distance of node *i* from the selected cluster heads
w_1	Corresponding weight of the energy-aware term in $T_{AEC}(i)$
w_2	Corresponding weight of the sink-distance-aware term in $T_{AEC}(i)$
w_3	Corresponding weight of the cluster-head-distance-aware term in $T_{AEC}(i)$

In the proposed LEACH-AEC protocol, there is totally six controllable parameters including w_1, w_2, w_3, t, α, and $d_{\min}$. These parameters should be optimized to gain the best performance from the LEACH-AEC. As mentioned above, the proposed methodology is an application-based approach. Therefore, the optimized value for the six controllable parameters should be tuned in such a way that the defined lifetime is maximized based on the application specifications. On the other hand, these parameters must be tuned based on the definition of the lifetime in the every specific application.

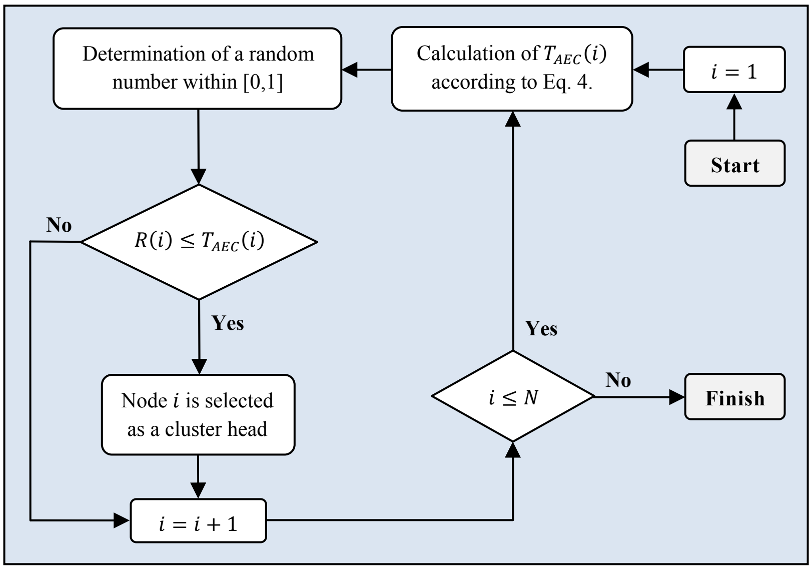

Fig. 1. The overall flowchart of the proposed cluster head selection process, in the every round.

As mentioned above, only the cluster head selection step in the setup phase is different from the original LEACH protocol. The overall flowchart of the proposed cluster head selection process in the every round can be summarized in Fig. 1. In Fig. 1, N is the number of all sensor nodes within the network, and i is the node number (i=1,2,…,N).

C. Multi-hop routing extension using A-Star algorithm

As mentioned above, the cluster-based protocols have good performance for routing in WSNs with small dimension. As the size of the network increased, the most data packets are transmitted in the multi-path fading model [7], in which, the energy consumption is related with d^4. Therefore, the cluster heads which are far from the sink would be rapidly dead, and the network lifetime will be reduced. We utilize the multi-hop routing extension using A-Star algorithm in LEACH-AEC, in order to cope with routing in large-size WSNs. A-Star [19] is a popular multi-hop routing algorithm, in which, the gathered data in an initial CH is transmitted either directly or hop-by-hop via the intermediate CHs until arrival the sink. In the each step, A-Star algorithm is used to select the next CH among all candidate nodes to transmit the gathered data packets.

In order to transmit the gathered data in the each cluster, the multi-hop routing is done hop-by-hop until arrival the data to the sink. In the each step, if the sink is within the radius distance d_{max}, the data packets are sent directly to the sink. Otherwise, a CH should be selected as the next intermediate node to handle the data through the sink. In this way, at first, all CHs which are within the radius distance d_{max} are chosen as the candidate CHs to be the next hop. Then, the next hop is selected using A-Star algorithm from the set of all candidates CHs. A-Star is based on the minimization of the sum of distances in data transmissions [19]. In A-Star algorithm, the function $f(n)$ is calculated according to

Eq. (8) for the each candidate CHs. Then, the CH which generates the minimum f, is selected as the next hop. The $f(n)$ for the candidate CH node n can be calculated as follows:

$$f(n) = g(n) + h(n) \tag{8}$$

Where $g(n)$ is the distance between the current CH and the candidate node n, and $h(n)$ is the distance from the candidate node n to the sink.

IV. PERFORMANCE EVALUTION

A. Communication model

In this paper, the first order radio model according to Ref. [7] is used as the communication model for the calculation of the energy consumptions of nodes. It is widely used in WSNs. In this model, depending on the transmission distance between the transmitter node and the receiver node, the free space model or the multi-path model is utilized. The energy consumption in the transmitter node for the transmission of a k-bit data packet with distance d-meter can be calculated as follows:

$$E_{TX}(k,d) = E_{TX-elec}(k) + E_{TX-amp}(k,d) = \begin{cases} k \times E_{elec} + k \times \varepsilon_{fs} \times d^2 & ,d < d_0 \\ k \times E_{elec} + k \times \varepsilon_{mp} \times d^4 & ,d \geq d_0 \end{cases} \tag{9}$$

Where E_{elec} is the energy consumption factor in the electronic circuitry, d_0 is a distance threshold defined as $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$. Depending on the transmission distance, ε_{fs} is used for the free space, and ε_{mp} is used for the multi-path model. Also, to receive a k-bit data packet, the energy consumption for the receiver node can be calculated as follows:

$$E_{RX}(k,d) = E_{RX}(k) = k \times E_{elec} \tag{10}$$

B. Simulation settings

All experiments were carried out in MATLAB environment. In order to justify the performance of the proposed LEACH-AEC routing protocol, we compared it against LEACH [7], LEACH-DT [11], and LEACH-EP [9], in terms of energy consumption, the number of data packets received in the sink, and the network lifetime. The proposed LEACH-AEC is performed in both levels: single-hop and with multi-hop extension of A-Star algorithm. In order to compare the mentioned routing protocols, 10 different workspaces are used, named WSN-1 to WSN-10. Each workspace composes of 200 heterogeneous sensor nodes randomly deployed in a topological area of dimension 200m×200m.

TABLE 1. NETWORK PARAMETERS

Networks Parameters	**Value**
Number of sensor nodes	200
Network size	200m×200m
Location of sink	100m,100m
Initial energy of nodes	1 J
E_{elec}	50 nJ/bit
ε_{fs}	100 pJ/bit/m^2
ε_{mp}	0.013 pJ/bit/m^4
d_0	87 m
Data packet	2000 bit
Control packet	50 bit

TABLE 2. OPTIMIZED VALUE OF THE CONTROLLABLE PARAMETERS OF THE PROPOSED PROTOCOL

Protocol	w_1	w_2	w_3	T	α	$d_{\min}$	$d_{\max}$
LEACH-AEC	0.6	0.1	0.3	0.9	3	0.1×M	87 m
LEACH-AEC with Multi-hop	0.6	0	0.4	0.9	3	0.1×M	87 m

All sensor nodes have the same battery and initial energy. There is only one sink located at the center of the workspace (100m, 100m). The network details can be seen in Table 1.

As mentioned above, the proposed LEACH-AEC protocol can be adapted for the each application, based on the application specifications. The proposed protocol has seven controllable parameters including w_1, w_2, and w_3 (in Eq. 4), t and α (in Eq. 5), $d_{\min}$ (in Eq. 7) and $d_{\max}$ (in A-Star algorithm). Here, we optimize these controllable parameters for those applications with heterogeneous sensor nodes, in which, the first node dies (FND) criterion is most important. Therefore, we tune LEACH-AEC in such a way that the FND lifetime is maximized. According to the obtained simulation results, the optimized parameters of LEACH-AEC protocol can be summarized in Table 2.

C. Simulation results

In order to capture the performance of the proposed protocol to prolong the network lifetime against LEACH, LEACH-DT, and LEACH-EP protocols, Figs. 2-4 statistically qualify them in WSN-1. Fig. 2 depicts the number of alive sensor nodes versus rounds. This figure clearly shows that the proposed routing algorithm is more stable than the other protocols, because node deaths begin later and continue linearly until all sensor nodes die. Also, Fig. 3 depicts the minimum energy of the network versus rounds. Finally, Fig. 4 depicts the total number of data packets received in the sink versus rounds.

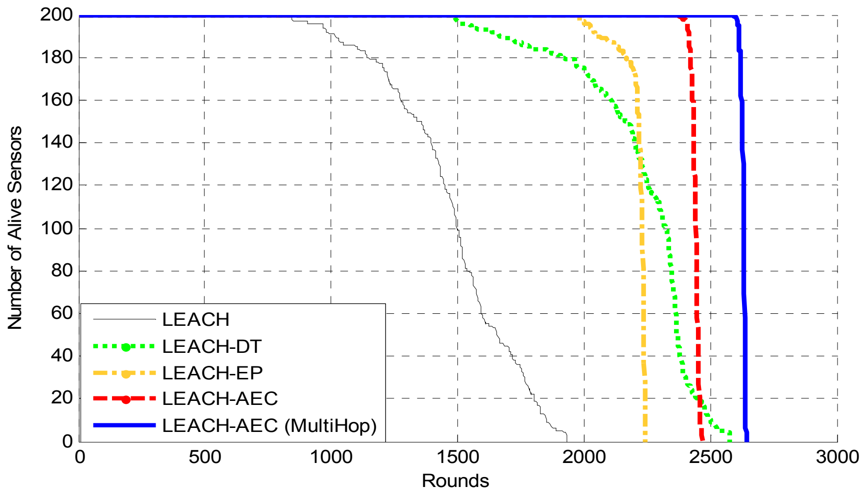

Fig. 2. Number of alive sensor nodes versus rounds, for WSN-1.

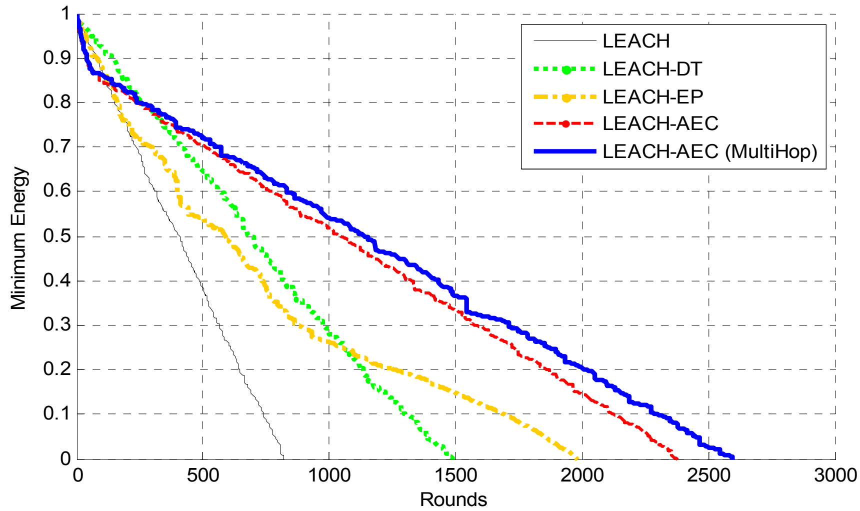

Fig. 3. Minimum network energy versus rounds, for WSN-1.

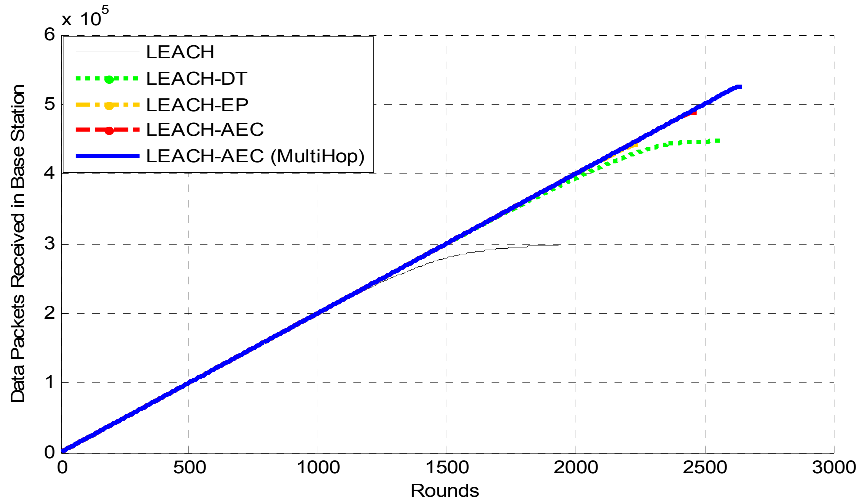

Fig. 4. Total number of data packets received in the sink versus rounds, for WSN-1.

TABLE 3. COMPARISON OF THE FND NETWORK LIFETIME

WSN #	LEACH	LEACH-DT	LEACH-EP	LEACH-AEC	LEACH-AEC with Multi-Hop
1	798	1456	1976	2382	2607
2	833	1474	2012	2377	2620
3	784	1401	1938	2347	2578
4	807	1447	1965	2368	2582
5	816	1488	1989	2401	2610
6	777	1408	1894	2312	2524
7	792	1467	1959	2371	2598
8	810	1504	1946	2367	2548
9	812	1512	1977	2390	2593
10	795	1489	1966	2361	2593
Average	802.4	1464.6	1962.2	2367.6	2585.3

TABLE 4. COMPARISON OF THE HND NETWORK LIFETIME

WSN #	LEACH	LEACH-DT	LEACH-EP	LEACH-AEC	LEACH-AEC with Multi-Hop
1	1501	2321	2233	2443	2637
2	1544	2378	2280	2439	2655
3	1473	2285	2203	2395	2608
4	1515	2333	2247	2475	2650
5	1522	2327	2260	2458	2678
6	1460	2259	2193	2377	2588
7	1506	2338	2245	2438	2651
8	1534	2350	2285	2478	2669
9	1542	2346	2277	2470	2680
10	1511	2344	2259	2453	2677
Average	1510.8	2328.1	2248.2	2442.6	2649.3

Also, the quantitative results included FND (Table 3) and HND (Table 4) can be summarized in Tables 3-4. Results in these tables clearly illustrate the positive impact of the proposed LEACH-AEC protocol to prolong the network lifetime. According to Table 3, the gain in the stable region of LEACH-AEC (with multi-hop extension) until FND is 222%, 77%, 32%, and 9%, as compared with LEACH, LEACH-DT, LEACH-EP, and LEACH-AEC (single-hop), respectively. Also, according to Table 4, the gain in the HND of LEACH-AEC (with multi-hop extension) is 75%, 14%, 18%, and 8%, as compared with LEACH, LEACH-DT, LEACH-EP, and LEACH-AEC (single-hop), respectively.

Finally, the effect of homogeneous/heterogeneous sensor nodes on the FND network lifetime is captured in Fig. 5. In the homogeneous energy networks, the same initial energy of 1 J is considered for all sensor nodes. In the heterogeneous energy networks two kinds of nodes are considered: simple nodes which have the initial energy of 1 J, and advanced nodes which have the initial energy of 2 J. Here, 100 simple sensor nodes (50%) and 100 advanced sensor nodes (50%) are used. According to the results in Fig. 5, the gain in the FND in LEACH and LEACH-DT is only 16% and 12%, respectively,

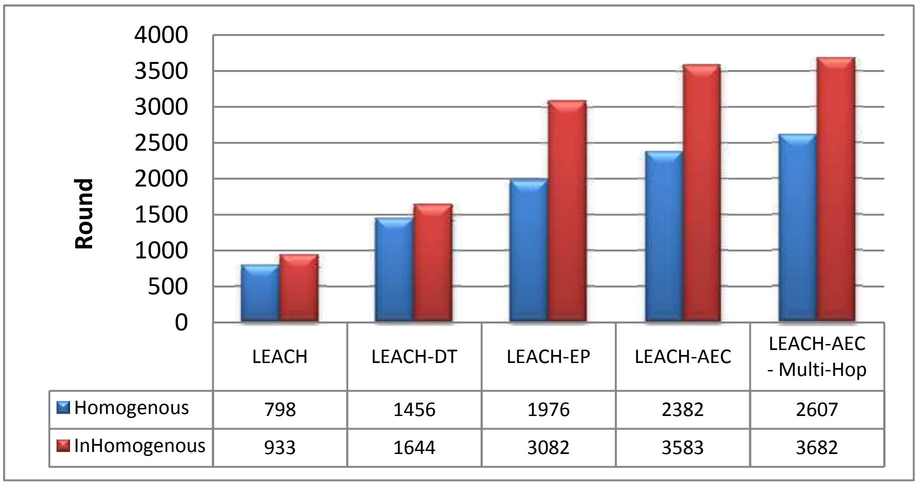

Fig. 5. Comparison of the effect of homogeneous/heterogeneous sensor nodes on the FND lifetime for WSN-1.

TABLE 5. COMPARISON OF THE AVERAGE DELAY IN CLUSTER HEAD SELECTION (MICRO SECONDS), IN EACH ROUND

WSN #	LEACH	LEACH-DT	LEACH-EP	LEACH-AEC	LEACH-AEC with Multi-Hop
1	117	160	193	432	619
2	115	158	194	440	625
3	127	167	201	448	648
4	122	163	189	448	638
5	126	168	202	455	626
6	119	158	189	429	636
7	118	159	191	433	628
8	123	167	185	446	634
9	121	159	197	433	626
10	118	157	188	439	647
Average	120.6	161.6	192.9	440.3	632.7

because the energy of sensor nodes is not considered in these protocols. However, the gain in the FND in energy-aware protocols LEACH-EP, LEACH-AEC, and LEACH-AEC with multi-hop is 55%, 50%, and 41%, respectively.

It is obviously that there is a trade-off between the network lifetime and the computational costs. Although the proposed algorithm prolongs the network lifetime very efficiently, it has extra overhead and delay to transmit data packets. Comparison of the average CPU time consumption (delay) in the each round for the different routing protocols can be summarized in Table 5. As seen, LEACH-AEC encounters higher computational complexity and consumes higher running time than the compared protocols. However, it can be ignored, due to the power of LEACH-AEC to prolong the lifetime.

V. CONCLUSION

In this paper, a new centralized cluster-based routing protocol named LEACH-AEC has been introduced, which takes into account more information from the current state of sensor nodes (including the residual energy of nodes, the distance from sink, and the distances between cluster heads) to select the optimal cluster heads. Also, the multi-hop routing extension via A-Star algorithm has been utilized in LEACH-AEC to cope with routing in large topological areas. The proposed protocol guarantees to form balanced clusters over the network. The main objective of LEACH-AEC is to prolong the network lifetime, based on the application specifications. Simulation results show that the proposed LEACH-AEC routing protocol outperforms the LEACH, LEACH-DT, and LEACH-EP algorithms with improved network lifetime, improved energy consumption, and improved number of transmitted data packets. The average gain in the network lifetime achieved via our algorithm is 85%, as compared with the three cluster-based protocols. The proposed protocol has been designed for WSNs with stationary sensor nodes and stationary sink. We plan to extend LEACH-AEC for routing in the networks with mobile sink or with mobile sensor nodes.

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