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Energy-Efficient Routing in Cluster-Based Wireless Sensor Networks: Optimization and Analysis

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Abstract— This paper investigates the energy-efficient routing in cluster-based wireless sensor networks (WSNs) by employing a linear programming formulation for the problem of minimizing energy consumption in such networks. This formulation considers energy consumption at different sensor nodes within a cluster and jointly optimizes the transmission energy of the sensor nodes to transmit data through a route with minimum energy. This approach has a big advantage to prolong the lifetime of the WSN. In order to study the energy-efficient routing in cluster-based WSN, several metrics are considered such as: number of clusters, maximum hop-count in each cluster, relay burden in cluster, and distribution of data aggregation among cluster-heads. Extensive simulations with different realizations are conducted to evaluate the proposed formulation. The results show that clustering reduces traffic flow, minimizes energy consumption, increase residual energy, and extend the lifetime of the sensor network. The proposed model offers a guarantee that the load of data routing in both intra-cluster communication and inter-cluster communication is balanced and distributed evenly. This research provides important design considerations in practical deployment of cluster-based sensor networks.

Keywords— Cluster-based, Energy consumption, Energy-efficient, Optimization, Routing, Wireless sensor networks.

I. INTRODUCTION

A wireless sensor network (WSN) is composed of a large number of sensors which are battery-powered devices connected wirelessly. Sensors are distributed in the field, collect sensory data (e.g., temperature, humidity, vibration, etc.), and collectively relay data to the base station (BS) [1]. WSNs have many important applications in environment, health care, industry, homeland security, etc. However, a significant limitation of sensor networks is their limited source of energy and short lifetime. In order to prolong lifetime, the flow of data in the network should be routed along a path that satisfies minimum energy consumption. Deigning such a network based on clustered architecture ensures the efficient utilization of limited capacity of energy. Unlike the layered architecture of WSN, where sensor nodes communicate with a single base station, the clustered architecture groups sensor nodes into disjoined non overlapping subsets called clusters, each cluster communicate with a single special node called cluster-head (CH), which communicates with the base station [2], [3] (Fig. 1).

Communication within a cluster is called intra-cluster communication, whereas communication between CHs and the base station is called inter-cluster communication. Clustering approach offers many benefits [3]-[7]. It results in network scalability, resource sharing and efficient use of constrained resources that gives network topology stability and energy saving attributes. Furthermore, it reduces communication overheads, allocates resources efficiently, decreases the overall energy consumption and reduces interference among sensor nodes. Also, it enables bandwidth reuse, and improves system capacity [6].

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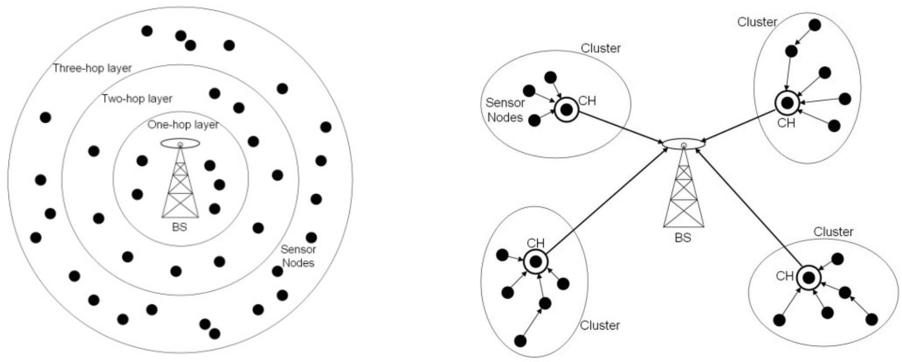


a) b)

Fig. 1. Wireless sensor network architecture: a) layered architecture, b) clustered architecture [2]. (BS: Base Station, CH: Cluster-Head)

This paper aims at investigating the measures to minimize the energy consumption of the WSN and the impact of clustering on energy consumption of the WSN. Instead of studying energy consumption in the typical sensor network, which is the focus of most previous literature such as [9]-[11], to name just a few, we investigate energy consumption in the cluster-based sensor network. For a WSN of N nodes, clusters are formed with a specific number of nodes (cluster's nodes) governed by a cluster-head. We minimized energy consumption in the cluster-based WSN by routing data through paths that consumed minimum energy in transmission and reception in both intra-cluster communication and inter-cluster communication.

The motivation for investigating energy consumption in cluster-based WSNs can be summarized as follows. In practical applications, some sensor nodes act as relay nodes that may have extremely data traffic through the routing process. Thus, the WSN can maintain its functionality as long as these sensors are maintained to still alive. To reduce energy consumption of relay nodes, a relay burden should be reduced. This could be achieved if we decompose the WSN into clusters. The number of relay nodes decreases and so does data traffic among cluster nodes in each cluster. Thus, energy consumption in each cluster of WSN will be minimized. The particular application in question determines how many clusters can form the WSN to maintain its functionality with minimum energy consumption.

The contributions of this paper can be summarized as follows. First, we provide an optimization formulation to minimize energy consumption for the cluster-based WSNs. Second, we investigate the impact of clustering on data routing and energy consumption. Our investigation shows that the clustering approach jointly with our optimization formulation minimizes energy consumption and consequently reduces the relay burden, and extends the network lifetime much more significantly than the network without clustering. The proposed approach offers a guarantee for an even distribution of data routing, and a balanced load among sensor nodes. This finding supports applications that require vast data traffic in routing.

The paper is organized as follows. In section II, some previous and related literatures are presented. In section III, the modeling of the problem and the definitions used in this research paper are explained. In Section IV, the formulation of the problem for minimizing energy consumption in cluster-based WSNs is described. In Section V, the results of the proposed formulation are simulated, evaluated and demonstrated. Finally, section VI presents the conclusion.

II. RELATED WORKS

Several previous works discussed the measures to minimize energy consumption of the WSNs using optimization formulations, such as [9]-[13], though they did not investigate the clustering approach in their formulations. Similar works were performed to maximize lifetime such as [14]-[16]. On the other hand, many previous works discussed energy-efficient routing in cluster-based WSNs such as [17]-[27]. However, most of such works do not consider an optimization formulation to minimize energy consumption in both intra-cluster communication and inter-cluster communication.

A number of the works which have studied the efficient utilization of clustering in routing are introduced in this section just to name a few. In [17], Low-Energy Adaptive Clustering Hierarchy (LEACH) is proposed. The main objective of LEACH is to select sensor nodes as cluster-heads in each round of communication randomly by rotation, so the energy consumption due to communication with the base station is distributed evenly among the sensor nodes. One of the main advantages of LEACH is that any node that has been selected as a cluster-head in certain rounds cannot be selected again for k rounds; where k is the desired percentage of cluster heads.

LEACH has no guarantee for the number of cluster head nodes and its placement; its performance is affected by a poor cluster forming. Therefore, the authors introduced an updated version called LEACH-centralized (LEACH-C) [19]. This modified protocol has better performance than LEACH since it employs a central control algorithm to form clusters, where cluster-heads can be distributed all over the sensor network to produce better clusters.

In [24], hybrid energy-efficient distributed clustering (HEED) is introduced. It is a clustering algorithm for multi-hop sensor network. This approach considers energy-efficient routing. In HEED, cluster-head selection is not random. The main purpose of this approach is to distribute cluster-heads uniformly in the sensor network. Cluster-heads are periodically selected based on residual energy and intra-cluster communication.

In [20], power-efficient gathering in sensor information systems (PEGASIS) is proposed. It is a nearly optimal chain-based protocol. In this work, the amount of energy spent per round is reduced; each node communicates only with a close neighbor and relays data to the base station. In [21], an improved algorithm of PEGASIS protocol introduced double cluster-heads in a wireless sensor network called PDCH to make a load balance among sensor nodes and prolong the network lifetime. Unlike PEGASIS, this approach implemented double cluster-heads in one chain and used a hierarchical structure to avoid long chains.

In [25], distributed weight-based energy-efficient hierarchical clustering protocol (DWEHC) is introduced. This approach forms a multi-level structure for intra-cluster communication. The main objective here is to form clusters with balanced sizes, and optimize the intra-cluster topology considering the location of the sensor nodes. In [26], position-based aggregator node election protocol (PANEL) is proposed. It is a position-based clustering routing protocol for WSNs. The main goal of PANEL is to provide a clustering approach for reliable applications. In [27], Energy Efficient and Cluster Based Routing Protocol for WSN protocol is proposed. This protocol provides an improvement of LEACH protocol, where it improves the set-up of clusters. This protocol employs a single-hop and multiple-hop hybrid routing to improve data transmission. It also provides an efficient exploitation of energy.

III. MODELING THE PROBLEM

A. Wireless Sensor Network Model

WSN is modeled as a connected directed graph *G (N, L)* (Fig. 2) [10]-[16]. *N* is a set of nodes $N = \{1,2,..., N\}$, and *L* is a set of links $L = \{L_{ij} \quad ; i \in N, j \in S_i\}$; S_i is the set of all nodes (neighboring nodes) that are connected to node *i*. Each node generates a number of bits called b_i. The data flow f_{ij} is the number of bits transmitted from node *i* to node *j* through the link L_{ij}. Each node has an initial energy E_{init}. Nodes in a multi-hop WSN may act as source nodes or relay nodes. WSN generally has one sink node (base station), but in cluster-based it has more than one sink node (cluster head) as shown in Fig. 3.

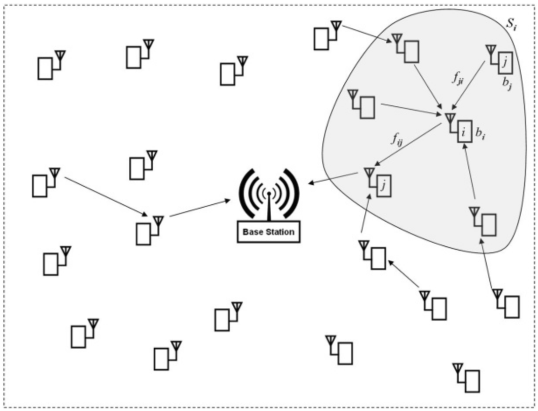


Fig. 2. WSN model; f_{ij} is the data flow, and S_i is the neighboring set

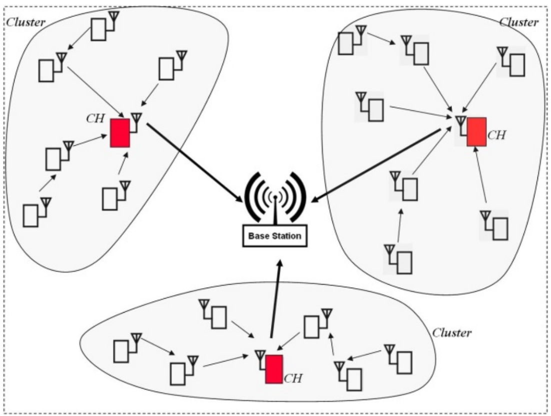


Fig. 3. Cluster-based WSN model; CH is the cluster-head

B. Energy Consumption Model

The energy consumption model employed in this research is similar to that one which was initially proposed by [18] (Fig. 4) and used in many previous works such as [15], [16], and [19]. When transmitting data (bits) from sensor node i (transmitter: T_x) to sensor node *j* (receiver: R_x), energy consumption at node *i* mainly involves operating radio electronics and amplifiers, while it involves only operating radio electronics at node *j*.

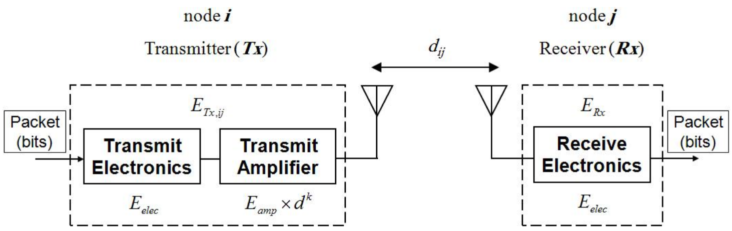


Fig. 4. Radio energy consumption model of communication system in WSN [18]

Based on Fig. 4, $E_{Tx,ij}$ is the required energy (*Joule/bit*) at node *i* to transmit one bit to node *j* over distance d_{ij} (Euclidean distance); E_{Rx} is the required energy (*Joule/bit*) to receive one bit; E_{elec} is the energy consumed by electronics (*Joule/bit*) which is distance-independent energy factor; and E_{amp} is the energy consumed by radio amplifier (*Joule/bit*) which is distance-dependent energy factor [15]. k is the path loss exponent ($2 \le k \le 4$) that is determined by the propagation channel and environmental conditions as mentioned in [15] and [18]. As a result, $E_{Tx,ij}$ and E_{Rx} are given by (1) and (2) respectively.

$$E_{Tx,ij} = E_{elec} + E_{amp} \times d_{ij}^{k} \tag{1}$$

$$E_{Rx} = E_{elec} \tag{2}$$

Consider that node *i* wants to transmit an amount of data (*bits*) to node *j* (f_{ij}). Energy consumption (*Joule*) at node *i* will be given by (3). On the other hand, consider that node *i* wants to receive an amount of data (*bits*) from node *j* (f_{ji}). Energy consumption (*Joule*) at node *i* is given by (4). As a result, total energy consumption (*Joule*) at node *i* can be given by (5) which represents the energy consumption of any node in the WSN.

$$E_{Tx,i} = \sum_{\substack{j=1 \\ i \neq j}}^{n} (E_{Tx,ij} \times f_{ij}) \tag{3}$$

$$E_{Rx,i} = E_{Rx} \sum_{\substack{j=1 \\ i \neq j}}^{n} f_{ji} \tag{4}$$

$$E_{cons,i} = E_{Tx,i} + E_{Rx,i} \tag{5}$$

In this research, the typical values which were employed are: $E_{elec} = 150 nJ/bit$, $E_{amp} = 0.0013 pJ/bit$, and $k = 4$ [18], [19].

IV. FORMULATION OF THE PROBLEM

In this section, the problem of minimizing energy consumption of cluster-based WSN is formulated using linear programming following the approaches in [8]-[16]. The formulation of the problem is given in (6) to (14). The variables and parameters used in the formulation are summarized in Table 1.

$$Objective : Minimize \quad \sum_{i=1}^{N} E_{cons,i} \quad ;\forall i \in N \tag{6}$$

Subject to

$$f_{ij} \geq 0 \quad ;\forall i \in N, \forall j \in S_i \tag{7}$$

$$E_{init,i} \geq E_{cons,i} \geq 0 \quad ;\forall i \in N \tag{8}$$

$$b_{CH,m} \geq 0 \quad ;\forall m \in C \tag{9}$$

$$\sum_{j=1,i\neq j}^{N-M} f_{ij} - \sum_{j=1,i\neq j}^{N-M} f_{ji} = b_i \quad ;\forall i \in (N-M), \forall j \in S_i \tag{10}$$

$$\sum_{j=1,i\neq j}^{N-M} f_{ji} = b_{CH,m} \quad ;\forall i \in (N-M), \forall j \in S_i, \forall m \in M \tag{11}$$

$$\sum_{m=1}^{M} b_{CH,m} = \sum_{i=1}^{N-M} b_i \quad ;\forall i \in (N-M), \forall m \in M \tag{12}$$

$$\sum_{j=1,i\neq j}^{N-M} (E_{Tx,ij} \times f_{ij}) + E_{Rx} \sum_{j=1,i\neq j}^{N-M} f_{ji} \leq E_{init,i} \quad ;\forall i \in (N-M), \forall j \in S_i \tag{13}$$

$$\sum_{j=1,i\neq j}^{N-M} (E_{Tx,ij} \times f_{ij}) + E_{Rx} \sum_{j=1,i\neq j}^{N-M} f_{ji} = E_{cons,i} \quad ;\forall i \in (N-M), \forall j \in S_i \tag{14}$$

TABLE 1
THE PARAMETERS USED IN THE LINEAR PROGRAMMING FORMULATION OF THE PROBLEM

Parameter	Description
$E_{cons,i}$	Energy consumption at node *i*
$E_{init,i}$	Initial energy level at node *i*
N	Number of nodes in WSN
f_{ij}	Total number of bits transmitted from node *i* to node *j*
b_i	Total number of bits generated at sensor node *i*
$b_{CH,m}$	Total number of bits aggregated at cluster-head *m*
M	Number of clusters which is the same as the number of cluster-heads
$N-M$	Number of none cluster-head nodes
$E_{Tx,ij}$	Required energy for node *i* to transmit one bit to node *j*
E_{Rx}	Required energy to receive one bit

Linear programming is an optimization formulation that has a linear objective function and a set of constraints [8]. The proposed formulation has the objective function (6) to minimize the total energy consumption of the cluster-based WSN. The constraints (7)-(9) are non-negative constraints. Constraint (10) is a flow conservation constraint, which states that at sensor node *i* the total number of bits transmitted to the neighboring set S_i minus those received from S_i is equal to the total number of generated bits b_i (Fig. 5) [9]. Constraint (11) states that the total number of bits received by the cluster-head from S_i is equal to the number of aggregated bits in cluster-head m. Constraint (12) states that the total number of aggregated bits at cluster-heads should be equivalent to the total number of bits generated in none cluster-head nodes; i.e., it is equal to $(N-M)\times b_i$. Constraint (13) states that energy consumption in sensor node i during the transmission and reception of data flow should not exceed the initial energy $E_{init,i}$. Constraint (14) calculates energy consumption in sensor node i during the transmission and reception of data flow.

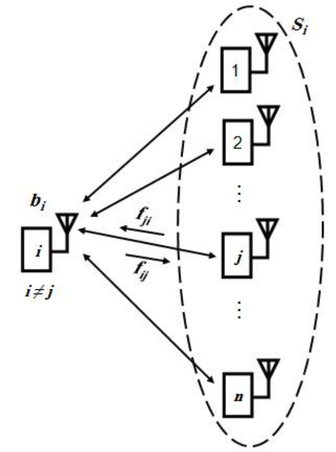
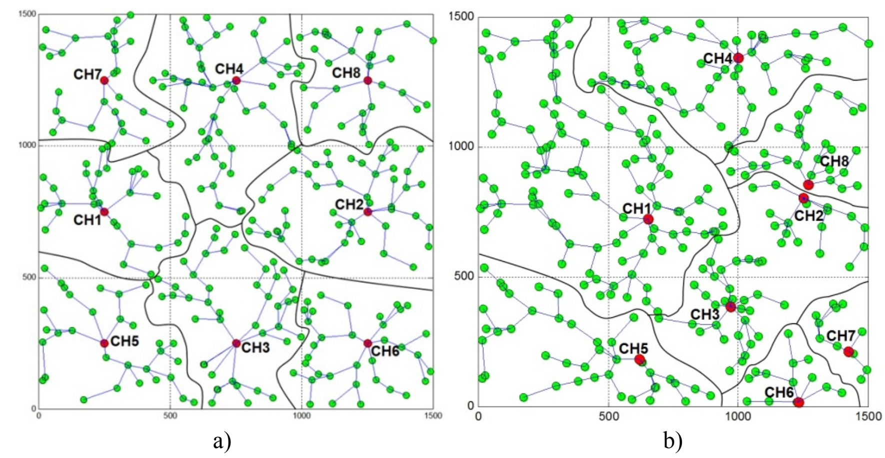


Fig. 5. Flow conservation constraint [9]

V. SIMULATION AND RESULTS

The proposed problem formulation model is solved and analyzed. A simulation is conducted for a sensor network consisting of 300 nodes deployed randomly in an area of 1500x1500 m^2. The radio range is set to 100m. The size of the packet that is generated at sensor node is set to be 500 bytes. The initial energy of each sensor node is set to 10 Joule. The base station is located at the center of the deployment area. Cluster-heads are deployed gradually in a grid-based described in Fig. 6a. We assume that cluster-heads are special nodes acting as an anchor or beacon nodes. Instead of using traditional random-clustering algorithms (Fig. 6b), grid-clustering is employed following similar approaches in [20]-[23], to name just a few, to reduce computational cost and provide good localization accuracy [22]. Also, grid-clustering identifies a high degree of malicious beacon signals [23]. Extensive simulations have been performed for other WSNs with different sizes; and the results are similar to what is presented in this study. A WSN should be selected carefully so as to have a feasible solution.



a) b)

Fig. 6. Clustering-approaches: a) grid-clustering, and b) random-clustering

In this study, a grid-clustering is considered for four cases described in Fig. 2: *case* 1) WSN with single base station located at center (one cluster), *case* 2) WSN with two cluster-heads (CH1 and CH2), *case* 3) WSN with four cluster-heads (CH1, CH2, CH3, and CH4), and *case* 4) WSN with eight cluster-heads (CH1, CH2, CH3, CH4, CH5, CH6, CH7, and CH8). Also, random-clustering is considered for the same cases in order to compare our work with previous works. For the first case (one cluster) both scenarios are the same.

Fig. 7 and Fig. 8 present data routing for the WSN of four cases; and the corresponding energy consumption distribution among sensor nodes compare grid-clustering with random-clustering. Several observations can be made based on these figures. First, by comparing Fig. 7a, Fig. 7b, Fig. 7c, and Fig. 7d, we observe that as the number of clusters increases the distribution of energy consumption of the nodes decreases.

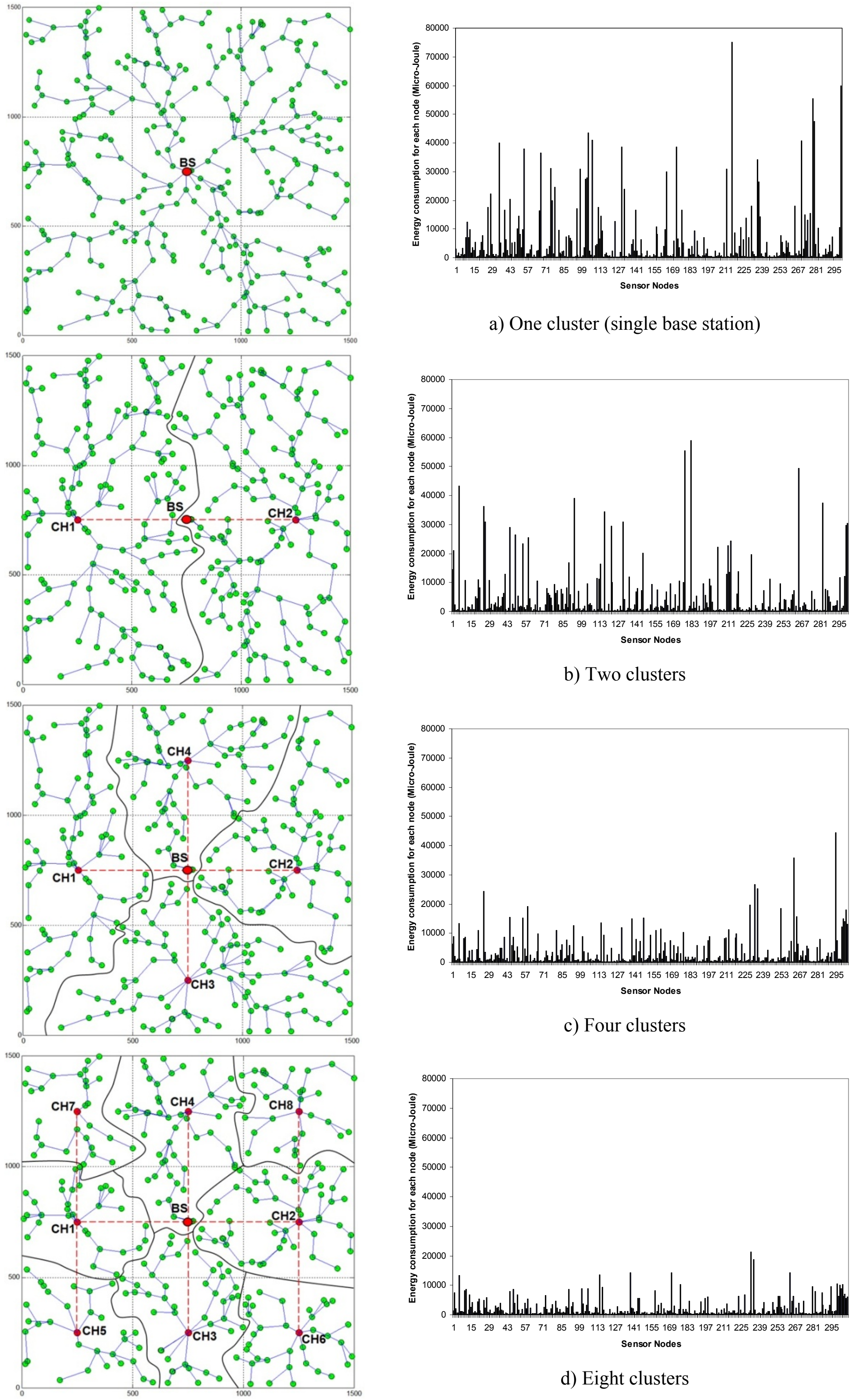
Second, it is observed that some nodes have consumed more energy than other nodes because these nodes have high traffic from the other nodes due to data routing. Third, the nodes which are close to the cluster-heads consume more energy than the leaf nodes. In addition, Fig. 8a, Fig. 8b, and Fig. 8c, which are related to random-clustering have the same behavior as grid clustering but with higher energy consumption among sensor nodes.

In the bottom line, we can say that clustering reduces traffic, minimizes energy consumption, increases residual energy, and consequently prolongs the lifetime of the sensor network.

Fig. 9 presents two scenarios of the results and solution for the problem of minimizing energy consumption in cluster-based WSN: grid-clustering and random clustering. Generally, Fig. 9 shows that the energy consumed by sensor nodes per cluster decreases significantly as the number of clusters increases. Based on the comparison between grid-clustering and random clustering, sensor nodes consume less energy in grid-clustering. This result could be explained by the fact that the weight of the relay and data-aggregation becomes less in grid-clustering since the nodes are closer to the cluster-head. In contrast, random clustering does not guarantee such issues because in some cases data flow will go through along path to reach the cluster-head.

Fig. 10 addresses the hop-count metric that can influence energy consumption in sensor networks. Generally, Fig. 10 shows that hop-count per cluster decreases significantly as the number of clusters increases. Based on the comparison between grid-clustering and random clustering, grid-clustering performs better in terms of hop-count. In grid-clustering, the decrease in the number of hops is not significant when employing two clusters. In random-clustering, the number of hops increases when employing two and four clusters; then it decreases. This result could be explained by the fact that sensor nodes become closer to the cluster-head in grid-clustering compared with random-clustering.

Fig. 11 studies another metric which has the capability to affect the energy-efficient routing called data aggregation in cluster-heads. We notice that data aggregation is distributed more evenly among cluster-heads in grid-clustering than in random clustering.



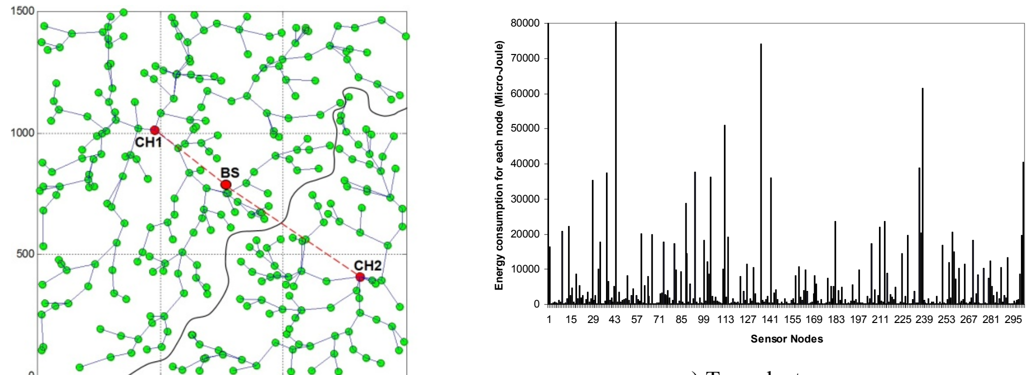
a) One cluster (single base station)

b) Two clusters

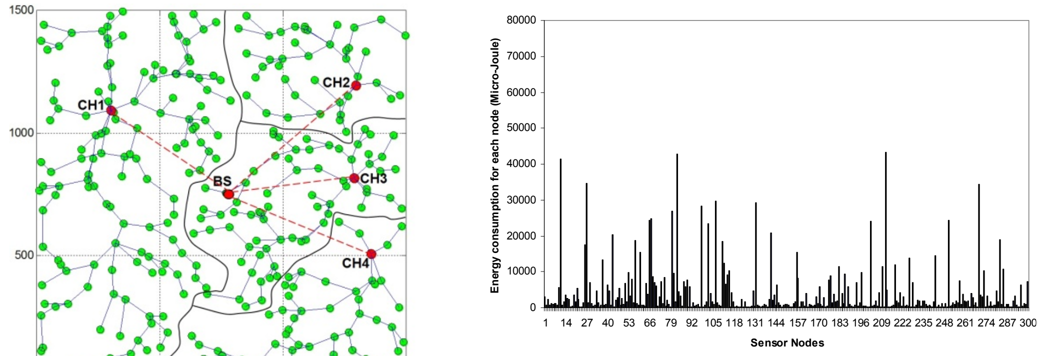
c) Four clusters

d) Eight clusters

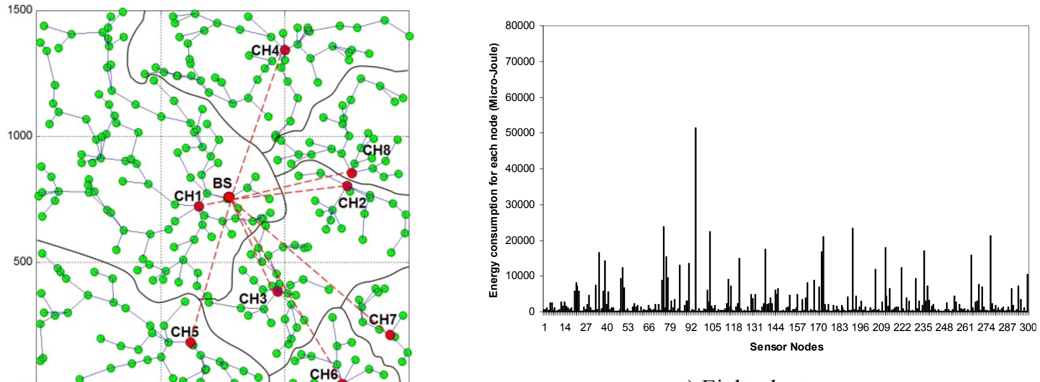
Fig. 7. Efficient-energy data routing for grid-clustered WSN of 300 nodes and the corresponding energy consumption distribution among sensor nodes with: a) one cluster (single base station), b) two clusters, c) four clusters, and d) eight clusters



a) Two clusters



b) Four clusters



c) Eight clusters

Fig. 8. Efficient-energy data routing for random-clustered WSN of 300 nodes and the corresponding energy consumption distribution among sensor nodes with: a) two clusters, b) four clusters, and c) eight clusters

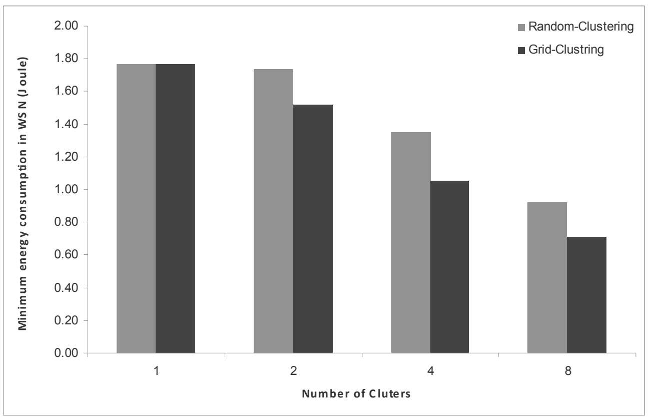


Fig. 9. Grid-clustering compared with random clustering for the minimum energy consumption in cluster-based WSN with 300 nodes

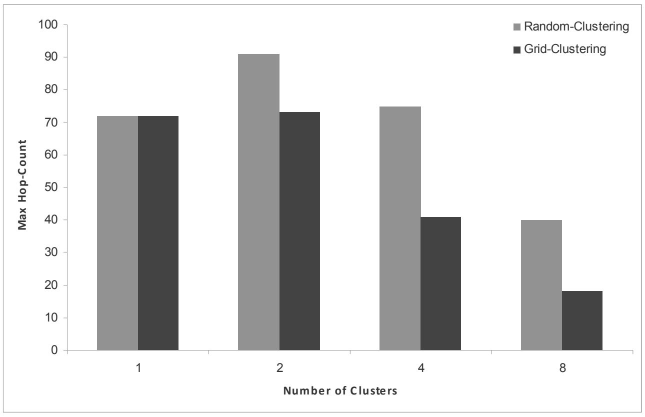
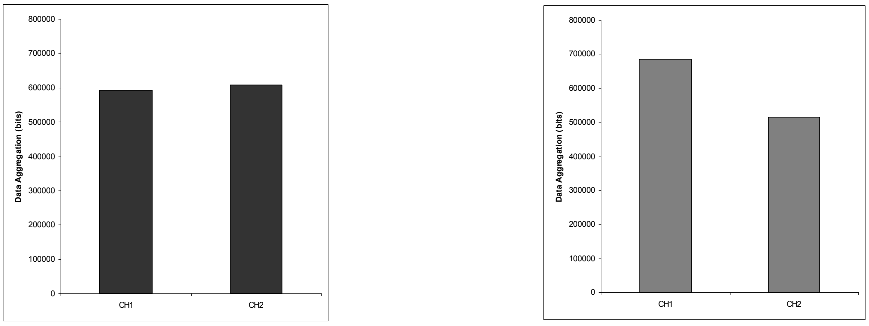
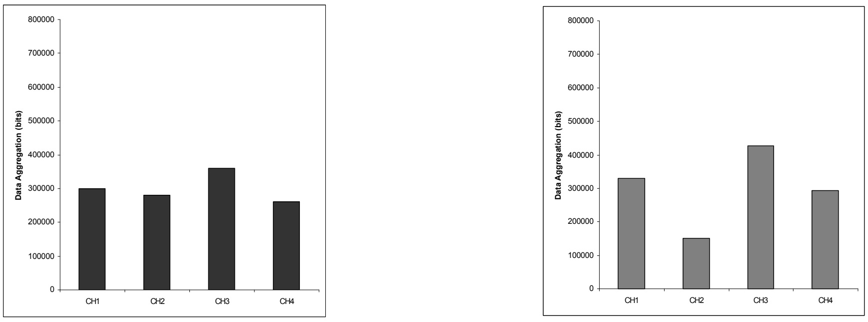


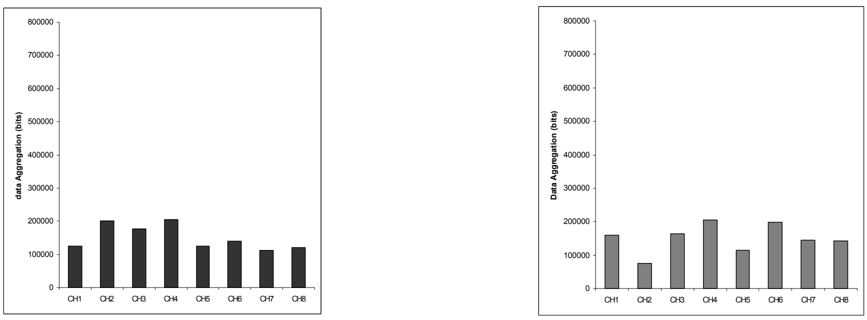
Fig. 10. Grid-clustering compared with random clustering for the maximum hop counts in cluster-based WSN with 300 nodes



a) Two clusters



b) Four clusters



c) Eight clusters

Fig. 11. The distribution of data aggregation among cluster-heads in WSN with 300 nodes for the two scenarios: grid-clustering (left) compared with random-clustering (right)

In Fig. 12, considering the two scenarios of grid-clustering and random-clustering, an estimation of the relationship between the number of clusters employed in a WSN and the minimum energy consumption in the cluster-heads is investigated. This relationship was addressed in [18] and [19]; and it states, generally, that as the number of clusters increases energy consumption in cluster-heads decreases for a specific range of clusters; then it increases. For our study, this range is around 2 to 4 in grid-clustering; and is around 2 to 3 in random-clustering. This investigation could clarify the relationship by the fact that when all nodes in the WSN act as cluster-heads, energy consumption would be very high. Yet, there is an estimated range of cluster-heads that ensure the reduction in energy consumption and hence energy-efficient routing. Additionally, if we consider a WSN with one cluster, sensor nodes will transmit data along a path with higher hop-count to reach the base station which consumes high energy. Alternatively, if we consider a large number of clusters with few aggregated data, cluster-heads will transmit data along high distance to reach the base station consuming high energy.

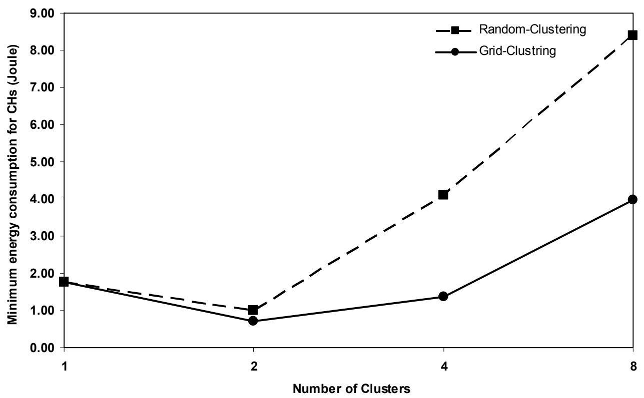


Fig. 12. The relationship between the number of clusters in cluster-based WSN of 300 nodes and energy consumption for cluster-head based on the scenarios of grid-clustering and random clustering

VI. CONCLUSION

In this paper, an efficient-energy routing for a cluster-based WSNs is investigated. This investigation was performed through a formulation of minimizing energy consumption in such networks. The study shows that most of the energy consumed by sensors is used to relay data traffic coming from other nodes; and the weight of the relay is much reduced when a clustering design is employed. Therefore, as the number of clusters increases the energy consumed by cluster's nodes decreases. A simulation was conducted to evaluate our approach considering two scenarios: grid-clustering and random clustering. The results illustrated that grid-clustering performs better than random-clustering in terms of energy consumption and hop-count. Generally, clustering approach has some limitations, as we should look for the best number of clusters to guarantee an efficient-energy routing. This finding helps develop the applications that require high data traffic in routing. This study can provide a useful guidance for the design of WSNs based on clustering.

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