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Optimized algorithm for balancing clusters in wireless sensor networks*

Mucheol KIM, Sunhong KIM, Hyungjin BYUN, Sangyong HAN‡

(*School of Computer Science and Engineering, Chung-Ang University 221, Heuk seok-dong, Dongjak-gu, Seoul 156-756, Korea*)

E-mail: {kmooky, shkim, kesarr}@ec.cse.cau.ac.kr; hansy@cau.ac.kr

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Abstract: Wireless sensor networks consist of hundreds or thousands of sensor nodes that involve numerous restrictions including computation capability and battery capacity. Topology control is an important issue for achieving a balanced placement of sensor nodes. The clustering scheme is a widely known and efficient means of topology control for transmitting information to the base station in two hops. The automatic routing scheme of the self-organizing technique is another critical element of wireless sensor networks. In this paper we propose an optimal algorithm with cluster balance taken into consideration, and compare it with three well known and widely used approaches, i.e., LEACH, MEER, and VAP-E, in performance evaluation. Experimental results show that the proposed approach increases the overall network lifetime, indicating that the amount of energy required for communication to the base station will be reduced for locating an optimal cluster.

Key words: Wireless sensor networks, Self-organizing sensor algorithm, Clustering algorithm, Optimization
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INTRODUCTION

With advances in wireless communication, extensive applications of wireless sensor networks have been found in measurements of temperature, humidity, lighting conditions, pressure, and noise (Akyildiz *et al*., 2002). Wireless sensor networks are also used for gathering data from places that are difficult to access such as deep sea or the South Pole. Hundreds of sensor nodes are used from airplanes and other vehicles to construct sensor networks. Sensors, though inexpensive, contain various limitations including computation capability and battery capacity (Estrin *et al*., 1999; Shin *et al*., 2006).

A variety of factors are to be considered for constructing a sensor network, such as network dynamics, node deployment, energy consumption, the data delivery model, node capabilities, and data aggregation (Akkaya and Younis, 2005). Numerous approaches have been proposed to reduce energy consumption, among which is mainly a multi-hop routing scheme, which transmits the data detected by a sensor to the destination via multiple node paths. Each node has a routing table that covers its communication range, and adjacent nodes determine which node the data should be forwarded to by considering the amount of remaining energy and the distance to the base station (Fig.1a) (Zhang and Maxemchuk, 2004).

The energy required for a transmission, $E_{TX}(d)$, is proportional to the square of distance (Heinzelman *et al*., 2002). Accordingly, the energy required for a node that has sensed data (e.g., node A) to transmit the data to a destination node (e.g., node C) via an intermediate node (e.g., node B) is less than the energy required for a direct transmission from node A to node C; i.e.,

$$E_{TX}(d=d_{AB})+E_{TX}(d=d_{BC})<E_{TX}(d=d_{AC}). \quad (1)$$

Another main approach is a clustering routing scheme, in which all the nodes in a network are

‡ Corresponding author
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grouped (or clustered). Every node belongs to one of the clusters; in each cluster there is a special node, called the cluster head (CH). Each non-cluster-head node (non-CH) collects and transmits data to a CH, and then the CH compiles and aggregates the messages.

The information is then relayed to the base station, making it a two-hop routing scheme. Important elements for the clustering routing scheme include the number of clusters, CH locations, and cluster density (Fig.1b). The method for selecting CHs and the amount of energy consumption are also important (Ohta *et al*., 2003).

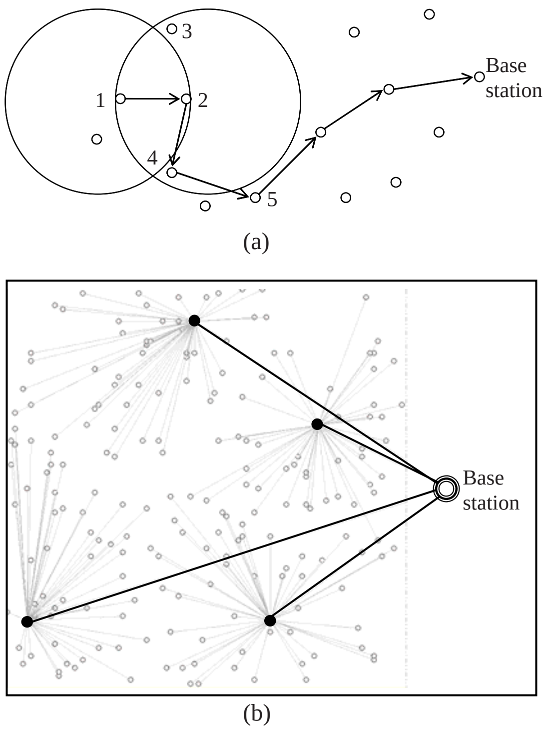

Fig.1 (a) Multi-hop routing protocol; (b) Clustering based routing protocol

This paper proposes an efficient algorithm for achieving cluster balance in the wireless sensor networks. Our algorithm is a novel protocol that uses a two-phase algorithm for selecting CHs to minimize energy consumption. In the first phase, temporary cluster heads (TCHs) are selected with a circulation algorithm. The second phase involves selecting CHs in the overlapping region constructed in the first phase. CHs are replaced with new ones in every round as they consume a lot of energy compared to other nodes.

RELATED WORKS

There are many studies that focus on optimizing energy consumption in wireless sensor networks. It rotates, as Heinzelman *et al*.(2000) suggested, the role of a CH using a random probability model to maintain energy balance of an entire network. In recent years, several improved clustering approaches were reported to resolve the imbalance of clusters (Kang *et al*., 2007; Wang *et al*., 2007). Younis and Fahmy (2004) proposed an approach that determines routes dynamically and arbitrates medium access for minimizing energy consumption.

On the other hand, some clustering approaches utilize location information without considering the energy model. Shin *et al*.(2006) and Chan and Perrig (2004) proposed an optimizing algorithm for cluster formation in wireless sensor networks; however, they used only location data of all the sensor nodes and did not take into account an energy consumption model. Park *et al*.(2007) also proposed an optimizing algorithm without an energy consumption model, focusing on the optimizing process with inefficient clusters.

Liu and Lin (2005) and Bandyopadhyay and Coyle (2003) introduced a hierarchical clustering approach by proposing the re-clustering strategy and a modified redirection scheme to increase the lifetime of a network. They formed hierarchical clusters and attempted to achieve an equality of density in each cluster. Bandyopadhyay and Coyle (2003) constructed a hierarchy level of clusters. Volunteer CHs are selected with a certain probability p, and the information is broadcasted within a certain range, say a k-hop. In their research, optimal p and k values were proposed for forming a hierarchical cluster.

Dhar *et al*.(2004) proposed a distributed clustering approach using a gateway node which is intersection between clusters in wireless sensor networks. Gateway nodes are selected through potential CHs. Among potential CHs a node that has received the largest number of messages through gateway nodes is elected as the CH (Xu *et al*., 2003).

Krishnan and Starobinski (2006) used a message-efficient clustering approach based on the concept of allocating growth budgets to neighbors. They brought forth a rapid algorithm, which is an enhanced persistent algorithm, and compared it with the expanding ring approach (Ramamoorthy *et al*., 1987). Note that the rapid algorithm is used for allocating budgets to neighbors, while the persistent algorithm for reallocating the shortfall until the bounding is reached or no more growth is possible.

Soro and Heinzelman (2009) put forward a very efficient self-organizing CH election approach based on node density and residual energy to improve the lifetime of a network.

OPTIMIZED ALGORITHM FOR BALANCING CLUSTERS IN WIRELESS SENSOR NETWORKS

Problems of previous studies

The LEACH (Heinzelman *et al*., 2000) algorithm is currently the most widely used algorithm for sensor network clustering. In order to equalize energy consumption, the algorithm uses the random rotation method for electing the CH. Furthermore, CH location is not fixed but to be newly selected every time to prevent a single node from quickly exhausting its energy. The problem of the LEACH algorithm is that head nodes are randomly selected, which results in irregular distances among the head nodes (Fig.2a). An increasing amount of energy thus yields in the delivery of messages from head nodes to a base station.

In order to overcome such problems of LEACH (Heinzelman *et al*., 2000), the LEACH-C (Heinzelman *et al*., 2002) algorithm allows the base station to intervene in the head selection process. In each round, every node sends its energy and location information to a base station which then selects head nodes using the simulated annealing algorithm (Murata and Ishibuchi, 1994) and notifies the information of head node selection to every node in a network. The LEACH-C approach consumes less energy than the conventional LEACH algorithm does. However, the problem with the LEACH-C algorithm is about its inability of using a self-organizing approach as against its allowing a base station to intervene in the cluster selection process, which forces all nodes into communicating with a base station in every round. Hence the energy required for communication, squarely in proportion with the distance, will increase significantly.

Kang *et al*.(2007) proposed an approach to improving the efficiency of the cluster by preventing neighbor nodes from becoming CHs in the same round. As compared with the consideration of regional information in this approach, a balanced clustering approach in Wang *et al*.(2007) was concerned with global information. The balanced clustering approach takes into account virtual partition which is calculated by mathematical approximation of the regional residual energy.

In this paper, we propose an efficient clustering approach considering both regional and global information (Fig.2b).

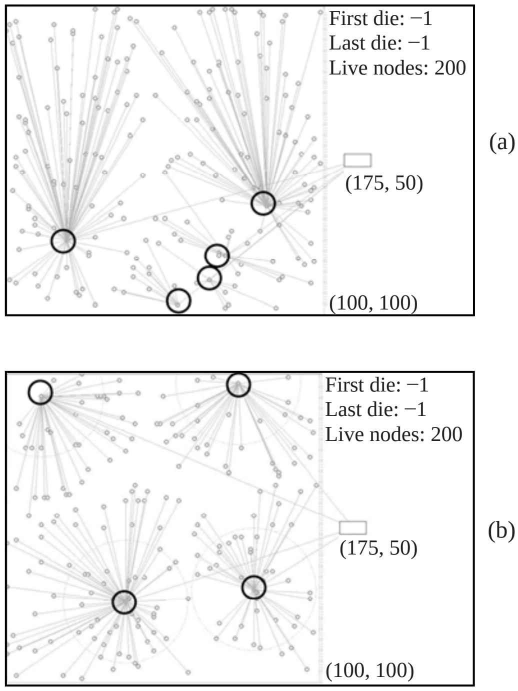

Fig.2 (a) Unbalanced clustering of LEACH; (b) An example of balanced clustering

Two-phase cluster creation algorithm using the overlapping region

Each node creates a communication region which is a circle area with a radius R from each node. Naturally overlapping regions develop in the process. If the nodes in the overlapping region become cluster centers, the distance imbalance in previous studies can be minimized.

This paper proposes an optimized algorithm for balancing clusters (OABC) using the overlapping region (Table 1). The algorithm consists of three stages: TCH election stage (1st phase), the optimal CH election stage (2nd phase), and the data transmission stage (Fig.3). We assume that the power configuration of sensor nodes can be programmable for this two-phase algorithm (Xing *et al*., 2005).

Table 1 Optimized algorithm for balancing clusters

1st phase:
1. Electing the temporary cluster head (TCH) using a random probability model.

2nd phase:

2. Advertising TCH election messages to the nodes within a radius of R.
3. Each node uses a TCH election message to determine whether it can be a CH.
   (1) Nodes that receive two or more TCH messages are candidates to become CHs.
   (2) Candidates use a probability model with its residual energy as a parameter.
   (3) In order to prevent redundant election of a head, an elected node is notified across the radius of $2R$.
4. A TCH that does not receive an election message from the head node elects itself as a CH. In other words, a TCH that receives an election message from the head node relieves itself of its role.
5. CHs broadcast to every node in their cluster that they have been elected as the CH.
6. Each node determines the cluster it will belong to and transmits a join message.
7. The head node creates a time division multiple access (TDMA) schedule and broadcasts it to every node in its cluster.

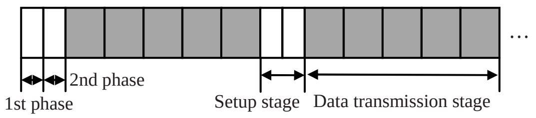

Fig.3 Time line showing the two-phase clustering algorithm

1. TCH election stage

This stage introduces a TCH election process. A TCH acts as a milestone for locating a CH to construct optimized clusters. The TCH is elected using Eq.(2), the random rotation method of the LEACH algorithm (Heinzelman *et al*., 2000):

$$P_{\mathrm{TCH}_i}(t)=\frac{k}{N-k\left[r \bmod (N/k)\right]}. \qquad (2)$$

2. Optimized CH election stage

This stage elects a CH using the TCHs selected in the previous stage. In order to identify an overlapping region, TCHs advertise the fact that they have become TCHs to all the nodes within a communication radius of R with a TCH election message (Fig.4). Nodes in the overlapping region will receive two or more TCH election messages and afterwards become CH candidates (Fig.5).

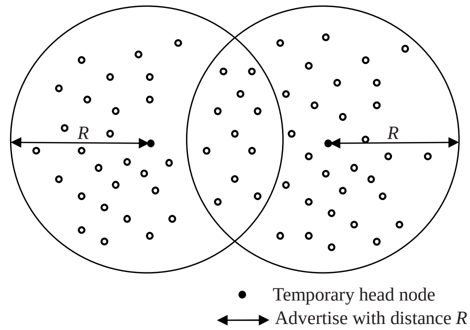

Fig.4 Advertising a temporary cluster head election message

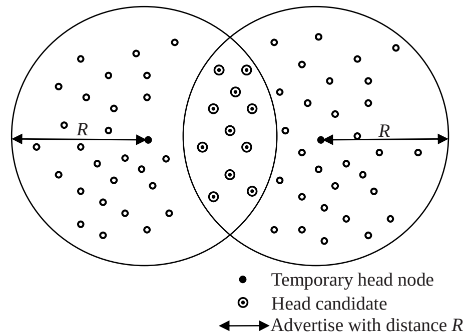

Fig.5 Optimal cluster head candidates in an overlapping region

The probability of becoming a CH for each candidate node is computed using the residual energy ratio and degree of overlapping, s. Residual energy factor, P_{e}, is calculated by means of total estimated residual energy of an entire network and that of a candidate from Eq.(3) (Fig.6):

$$P_{\mathrm{e}}=\frac{E_{\text{Candidate\_node}}}{E_{\text{Entire\_network}}}\times s. \qquad (3)$$

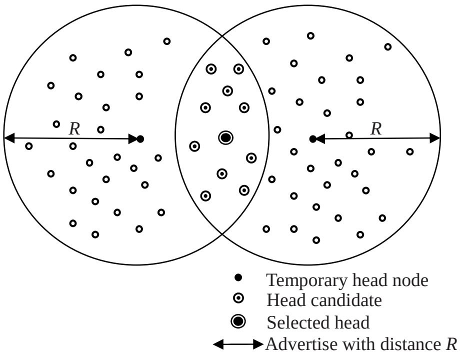

Fig.6 Cluster head candidates in an overlapping region

The probability of becoming a CH, P_{CH}, is adjusted by incorporating a degree of overlapping from Eq.(4). Degree of overlapping is represented by the number of TCH election messages received, n_{TCH}.

$$P_{\mathrm{CH}}=P_{\mathrm{e}}\cdot n_{\mathrm{TCH}}. \tag{4}$$

The probability of becoming a CH, P'_{CH}, is again re-adjusted by Eq.(5) so that it would not exceed 1.

$$P'_{\mathrm{CH}}=\min(1,\ P_{\mathrm{CH}}). \tag{5}$$

Each elected CH advertises itself to the nodes within a radius of 2R (Fig.7) via a CH election message. The message is intended to prevent adjacent candidates from becoming a duplicate CH. Therefore, the candidates receiving the CH election message do not elect themselves as CHs.

If an optimal CH does not exist in the vicinity and there are TCHs that have not received optimal CH election messages, the TCHs will elect themselves as optimal CHs. This is a part of an effort to achieve a balance in communication distances of the entire network.

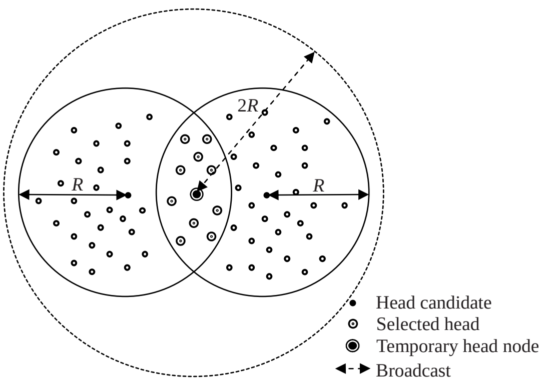

Fig.7 Cluster head advertising message for preventing redundant election

As a result, this algorithm iterates two processes and one exception handling routine for electing balanced CHs. They are both TCH election processes, one for preventing redundant election of a CH and the other for exception handling (Fig.8).

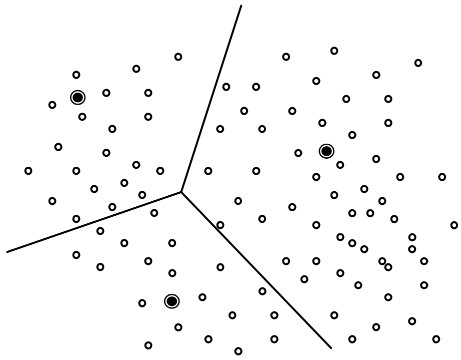

Fig.8 Optimal clusters obtained using the proposed algorithm

Elected CHs broadcast messages to every node to notify the final outcome that they have been elected. Upon receiving the messages, every non-CH joins the closest CH. Then the CH performs TDMA scheduling according to the order of how its member nodes get joined. The TDMA schedule is transmitted to every member of the cluster.

Data transmission stage

Once the setup phase is complete, the data transmission stage begins like the one illustrated in Fig.3. In order to minimize energy consumption, non-CHs are in sleep mode except for in the duration when they must stay awake according to the TDMA schedule. This consumes a minimum amount of energy, and no message can be exchanged during a sleep mode. Each node wakes up from a sleep mode on its turn according to the set sequence, collects information that it was pre-assigned with, and sends the information to the CH.

Each CH maintains the switch-on state during the data transmission phase, collects and aggregates information from every member of the cluster, and sends the compiled information to a base station. When the last node completes a transmission based on the TDMA schedule, the CH aggregates the data acquired from cluster member nodes and the information is sent to a base station. Since the CH consumes a significant amount of energy to maintain the switch-on state and sustain communication with a base station, a new CH is elected in every round.

EXPERIMENTAL RESULTS

Experimental setup

Table 2 defines the parameters required for the experiments (Heinzelman *et al*., 2002). The energy needed to receive a message is the electronic energy of 50 nJ/bit. On the other hand, both electronic energy and amplifying energy are in need to send a message. If d is smaller than d_0, amplifying energy uses the free space model; if d is greater than d_0, the multipath fading model is used. Finally, the energy required for data aggregation is 5 nJ/(bit·signal) (Heinzelman, 2000).

Table 2 Constants used in the experiments

Constant	Description	Value
E_{elect}	Electronic energy	50 nJ/bit
ε_{fs}	Free space model for amplifying ($d<d_0$)	10 pJ/(bit·m^2)
ε_{mp}	Multipath fading model for amplifying ($d\geq d_0$)	0.0013 pJ/(bit·m^4)
E_{DA}	Energy for data aggregation	5 nJ/(bit·signal)

Two hundred nodes were distributed and installed in a region of 100 m×100 m. With the assumption that the base station is located sufficiently far from every node, the base station location was set at (50, 175). Data messages were transmitted in the unit of 4000 bits (500 bytes).

In these experiments, the proposed approach OABC was compared with LEACH (Heinzelman *et al*., 2000), MEER (Kang *et al*., 2007), and VAP-E (Wang *et al*., 2007). MEER and VAP-E are advanced algorithms based on LEACH. We also needed to define the hop size of the TCH and the TCH election probability of OABC: 25 m for TCH's hop size and 0.05 for the TCH election probability. Since the experiments were conducted with 200 nodes, 10 was regarded as the optimal number of TCHs because the clusters of the sensor networks were divided into smaller units compared with the conventional LEACH algorithm.

Theoretical analysis

This subsection presents a mathematical analysis for these experiments. Each node estimates the residual energy of an entire network with its location information. Assumptions to estimate energy consumption are shown in Table 3.

Table 3 Assumptions to estimate residual energy of a network

1. All nodes have the same energy consumption required to communicate with BS which is located sufficiently far.
2. All non-CHs have the same energy consumption required to communicate with TCH or CH.
3. All nodes have the same energy consumption required to broadcast.
4. The number of optimal clusters in every round is 4, which is a heuristic value.
5. The number of temporary clusters in every round is 8, which is also a heuristic value.
6. The energy dissipation for communicating with the base station follows the multipath fading model.

Table 4(a) shows the estimated energy consumption for each non-CH, TCH, and CH. In a setup state, energy consumption is reckoned for all three different types of nodes. In a steady state, estimation has been made for two types of nodes, i.e., CH and non-CH. In a setup state non-CHs spend energy for electing TCHs and CHs. The energy consists of four different kinds. The first one is for receiving a message for TCH election (E_{RMTE}) and the second for receiving a message for preventing redundancy (E_{RMPR}). The third one is for receiving a broadcasting message for CH election (E_{RBCE}) and the last for a join message (E_{JOIN}). For TCHs they need additional energy for advertising (E_{AMTE}) and receiving (E_{RMTE}) a message for TCH election in addition to all the energy required by non-CHs. The CH also consumes the energy for broadcasting an election and scheduling process. Energy for broadcasting a message for CH election is denoted by E_{BMCE} and the one for TDMA scheduling message by E_{BTSM}. The CH also needs energy for receiving a join message (E_{RJM}) and for receiving a message for TCH election (E_{RMTE}). The total number of non-CHs in a cluster is denoted by α.

Equations to estimate the residual energy in a steady state are also shown for CHs and non-CHs in Table 4(b). CHs spend energy for communicating with a base station (E_{commBS}) and receiving a message to the CH (E_{RMCH}) from a base station. The CH also needs energy for aggregating data (E_{DA}) in a steady state. Non-CHs consume only energy required to advertise a message to the CH (E_{AMCH}). The CH election process is very efficient as unnecessary communications are excluded.

Table 4 Ordered equations to estimate residual energy of an entire network

(a) Setup state

$E_{non\text{-}CH}=E_{RMTE}+E_{RMPR}+E_{RBCE}+E_{JOIN}$

$E_{TCH}=E_{non\text{-}CH}+E_{AMTE}+E_{RMTE}$

$E_{CH}=E_{BMCE}+E_{BTSM}+\alpha E_{RJM}+E_{RMTE}$

(b) Steady state

$E_{CH}=E_{commBS}+\alpha E_{RMCH}+E_{DA}$

$E_{non\text{-}CH}=E_{AMCH}$

Results of the proposed clustering algorithm

Table 5 lists the results of the experiments involving varying the amount of initial energy to measure a sensor network's lifetime. The lifetime was measured by the round number at which the first or the final node died. OABC's lifetime measured when the first node died was about 1.6 times longer than LEACH's, 1.3 times better than MEER's, and 1.15~2.67 times that of VAP-E's. It was observed that the performance of VAP-E was highly dependent on the initial energy. Measurements based on when the last node died showed similar results. OABC showed the best performance among the four protocols in every case.

Table 5 Results of a network lifetime comparison of OABC with other three algorithms

Energy (J/node)	Protocol	Round number at which the first node dies	Round number at which the last node dies
0.5	LEACH	173	344
	MEER	237	461
	VAP-E	125	418
	OABC	296	592
1.0	LEACH	347	660
	MEER	387	875
	VAP-E	349	811
	OABC	545	1260
2.0	LEACH	713	1344
	MEER	933	1797
	VAP-E	1019	1787
	OABC	1179	2514

Fig.9 shows the lifetime of the four clustering approaches. In the first 1000 rounds, the entire nodes were alive for MEER, VAP-E, and OABC protocols, but only three quarters of nodes were alive for the LEACH protocol. In the 1500th round, most of the nodes died in the LEACH algorithm and three quarters of nodes were alive for MEER and VAP-E.

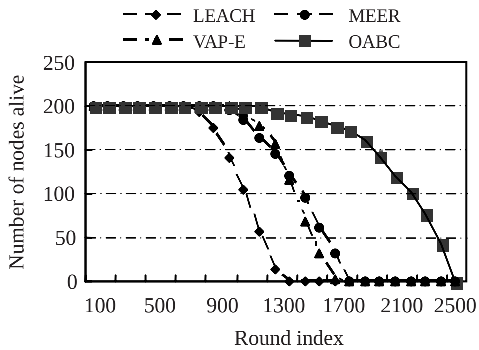

Fig.9 Lifetime comparison of OABC with other three algorithms

On the other hand, most of the nodes in the OABC algorithm prolonged the lifetime of networks in the same condition. At near the 2000th round, three quarters of the nodes were still alive when OABC was applied and most of the nodes died in other algorithms. If the lifetime of a wireless sensor network is defined as the length of time for which at least 75% of all nodes are alive, the proposed approach extends the lifetime by 43%~200%. After 2000 rounds, nodes in OABC drained the entire energy rapidly. As clustering was constructed to balance energy consumption among all the nodes, most of the nodes used up energy in a similar time. It makes the proposed balanced clustering algorithm more efficient than other clustering approaches do.

Fig.10 displays the average energy dissipation for each node in a single round. In the LEACH algorithm each node consumed about 1.734 mJ, and 0.864 mJ in OABC. It was also reported that each node consumed about 1.321 mJ and 1.172 mJ for MEER and VAP-E algorithms, respectively. The results showed that much less energy was consumed in OABC than in other schemes, namely 50% of LEACH's, ca. 65% of MEER's, and ca. 73% of VAP-E's.

Fig.11 illustrates another experiment in which we compared the lifetime of different algorithms by varying the number of sensor nodes.

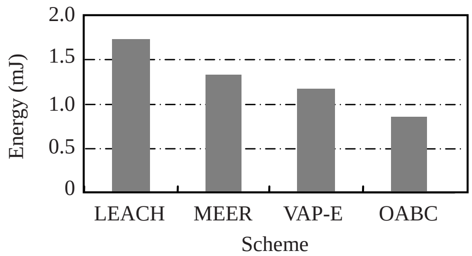

Fig.10 Average energy dissipation of each node in a single round

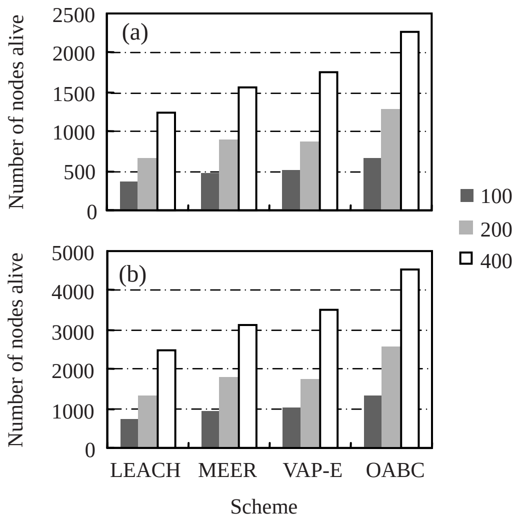

Fig.11 Lifetime of a sensor network with varying numbers (100, 200 and 400) of sensor nodes
(a) Rounds when the first node dies; (b) Rounds when the last node dies

For all algorithms the lifetime of a sensor network gradually increased as node density increased. However, the inclination of OABC was sharper than that of MEER and VAP-E. This experiment also showed that performance of OABC was not affected by the size of the network.

Summary of experiments

The proposed algorithm OABC was compared with three different well-known approaches. Defining the lifetime of a sensor network as the length of time for which at least 75% of all the nodes being alive, the proposed approach extended the lifetime of a network by 43%~200% in an experiment. The average energy dissipation for each node in a single round was also measured. The results showed that much less energy was consumed in OABC than in other schemes. It was reported that about 50% to 73% of energy was consumed for each node. Similar results were also reported in the experiments with varying node densities. Overall, the proposed algorithm showed much better results in every aspect of measurement criteria, and also demonstrated that balanced clustering and balanced energy consumption of each node have a strong impact on the lifetime of a sensor network.

CONCLUSION

In this paper a new algorithm is proposed to achieve a balanced clustering in a wireless sensor network. The proposed approach uses a two-phase process for selecting cluster heads to find an optimal configuration to minimize energy consumption in a network. In the first phase temporary cluster heads are selected with a circulation algorithm. The second phase involves choosing cluster heads to minimize energy consumption of all the nodes in a cluster. To achieve a balanced clustering, cluster heads are picked out among the nodes located in an overlapping region constructed in the first phase. Cluster heads are selected among the candidate nodes in an overlapping region using a probability model with their residual energy as a parameter and a degree of overlapping. Cluster heads are replaced with new ones in every round because of high energy consumption of cluster heads. The proposed algorithm was implemented and evaluated with various experimental data and compared with three known and widely used algorithms. Experimental results showed that the proposed approach extended the life cycle of a sensor network significantly, reduced the total energy consumption of a network, and achieved a uniform energy consumption of every node in a network.

The contribution of this paper lies in its provision of an automatic cluster head selection process and of minimum energy consumption by maintaining equidistance among cluster heads. Also, a framework has been figured out to create efficient clusters in the multi-hop clustering technique by enabling communications among clusters. The proposed approach can be further used for an efficient integration of existing clusters.

This approach, however, does not handle newly created nodes or an expiration of existing nodes due to an abrupt malfunctioning. Therefore, studies that incorporate scalability and flexibility should be conducted in the future. Extending our proposed approach to an automatic multi-hop clustering technique will be an interesting research topic.

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