Journal of Computer and System Sciences 77 (2011) 282–292

Contents lists available at ScienceDirect

Journal of Computer and System Sciences

www.elsevier.com/locate/jcss

Adaptive decentralized re-clustering protocol for wireless sensor networks

Fuad Bajaber *, Irfan Awan

Department of Computing, University of Bradford, Richmond Road, Bradford, West Yorkshire, BD7 1DP, UK

ARTICLE INFO

Article history:
Received 8 June 2009
Received in revised form 21 September 2009
Available online 2 February 2010

Keywords:
Wireless sensor networks
Adaptive clustering
Energy efficiency
Clustering protocol

ABSTRACT

Wireless sensor networks are composed of a large number of sensor nodes with limited energy resources. One critical issue in wireless sensor networks is how to gather sensed information in an energy efficient way since the energy is limited. The clustering algorithm is a technique used to reduce energy consumption. It can improve the scalability and lifetime of wireless sensor network. In this paper, we introduce an adaptive clustering protocol for wireless sensor networks, which is called Adaptive Decentralized Re-Clustering Protocol (ADRP) for Wireless Sensor Networks. In ADRP, the cluster heads and next heads are elected based on residual energy of each node and the average energy of each cluster. The simulation results show that ADRP achieves longer lifetime and more data messages transmissions than current important clustering protocol in wireless sensor networks.

1. Introduction

A wireless sensor network is composed of a large number of sensor nodes and a base station. The nodes in a wireless sensor network are usually deployed randomly inside the region of interest. The base station is engaged to give commands to all the sensor nodes and gather information from the sensor nodes. Typically, a sensor node is a tiny device that includes three basic components: a sensing subsystem for data acquisition from the physical surrounding environment, a processing subsystem for local data processing and storage, and a wireless communication subsystem for data transmission [2,5,11,13]. Wireless sensor nodes have many limitations, including modest processing power, little storage, and limited power source. The base station is usually much more powerful than sensor nodes and has power supplied. On the other hand, the base station needs to collect the sensed information from the sensor nodes and send it back to the user. Because wireless sensor nodes are low-powered, the constraint on the power consumption is an important issue when designing wireless sensor network protocols.

Clustering has been well received as an effective way to reduce the energy consumption of a wireless sensor network. Clustering is defined as the process of choosing a set of wireless sensor nodes to be cluster heads for a given wireless sensor network. Therefore, data traffic generated at each sensor node can be sent via cluster heads to the base station [3,6,12,15,17]. Clustering is also used for data aggregation, where the cluster heads aggregate the information collected at the cluster members.

We introduce ADRP, for electing cluster heads and next heads in wireless sensor networks. The selection of cluster heads and next heads are weighted by the remaining energy of sensor nodes and the average energy of each cluster. ADRP is an adaptive clustering protocol; cluster heads rotate over time to balance the energy dissipation of sensor nodes.

* Corresponding author.
E-mail addresses: F.G.Bajaber@Bradford.ac.uk (F. Bajaber), I.U.Awan@Bradford.ac.uk (I. Awan).

0022-0000/$ – see front matter
doi:10.1016/j.jcss.2010.01.007

The remainder of this paper is organized as follows. Section 2 provides an overview of related work. In Section 3, we define the system model. In Section 4, we present ADRP. Section 5 provides details of the algorithm. Section 6 presents the simulation setup and results. Section 7 concludes the paper and outlines future work.

2. Related work

PEGASIS [8] is an improvement of the well-known LEACH protocol for clustering based communication in sensor networks. Rather than forming multiple clusters, PEGASIS forms chain from sensor nodes so that each node transmits and receives from a neighbor and only one node is selected from that chain as leader node to transmit to the base station. The main objectives of PEGASIS are to increase the lifetime of network and allow only local coordination between nodes that are close together so that the bandwidth consumed in communication is reduced. PEGASIS eliminate the overhead caused by dynamic cluster formation in LEACH, and decrease the number of transmissions and reception by using data aggregation although the clustering overhead is avoided. However, this achievement faded by the excessive delay introduced by the single chain for the distant node.

In [1] the operation of LEACH is divided into rounds and each round separated into two phases, the set-up phase and the steady-state phase. In the set-up phase, each node decides whether or not to become a cluster head for the current round. This decision is based on the threshold $T(n)$ given by

$$T(n)=\begin{cases}\frac{p}{1-p\times(r \bmod \frac{1}{p})} & \text{if } n\in G,\\ 0 & \text{otherwise},\end{cases} \tag{1}$$

where p is the predetermined percentage of cluster heads (e.g., $p=0.05$), r is the current round, and G is the set of nodes that have not been cluster heads in the last $1/p$ rounds. Cluster head broadcasts an advertisement message to the rest of the nodes. Depending on the signal strength of the advertisement messages, each node selects the cluster head it will belong to. The cluster head creates a Time Division Multiple Access (TDMA) scheme and assigns each node a time slot. In the steady-state phase, the cluster heads collect data from sensor nodes, aggregate the data and send it to the base station.

LEACH-Centralized [4] uses a centralized clustering algorithm. In setup phase, the base station receives all information about each node regarding their location and energy status. The base station runs local algorithm for the formation of cluster heads and clusters and broadcasts a message that contains the cluster head ID for each node. The steady-state phase of LEACH-C is identical to that of the LEACH protocol. Because the clustering setup is done every round a significant amount of energy is consumed and communication latency is increased.

In [4] LEACH with Fixed clusters (LEACH-F) the base station uses the same algorithm used in LEACH-C to form the clusters then LEACH-F uses fixed clusters that are formed once in the first setup phase by the base station. The cluster head position rotates, and every node can become cluster head of its cluster. The fixed clusters do not allow new nodes to be added to the network, and the nodes performance is not affected by nodes dying.

TEEN [9] designed for time-critical applications to respond to changes in the sensed attributes such as temperature. After the clusters are formed, the cluster head broadcasts two thresholds to the nodes. These are hard and soft thresholds for sensed attributes. The hard threshold aims at reducing the number of transmissions by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The soft threshold will further reduce the number of transmissions if there is little or no change in the value of sensed attribute. One can adjust both hard and soft threshold values in order to control the number of packet transmissions. The advantage of this scheme is its suitability for time critical application and also the fact that it significantly reduces the number of transmission.

APTEEN [10] is an extension to TEEN and aims at capturing periodic data collections and reacting to time-critical events. Once a node senses a value beyond hard threshold, it transmits data only when the value of that attribute changes by an amount equal to or greater than soft threshold. The main drawbacks of TEEN and APTEEN are the overhead and complexity associated with forming clusters at multiple levels.

HEED [16] provides balanced cluster heads and smaller sized clusters. They use two radio transmission power levels; one for intra-cluster communication and the other for inter-cluster communication. HEED does not select cluster head nodes randomly. Sensor nodes that have a high residual energy can become cluster head nodes.

Centralized Dynamic Clustering CDC [18] organizes the network into clusters. Each cluster selects a node that serves as the cluster head. The cluster head is responsible for collecting the data from all the cluster members, aggregating the data, transmitting information to the base station and selecting new cluster head for next round. If any node die in cluster the cluster head sends message to base station to forms clusters, otherwise cluster heads use energy levels to select new cluster heads with max energy for next round.

3. System model

In this protocol, the sensor nodes periodically switch on their sensors and transmitters, sense the environment, and transmit the data. The wireless sensor network consists of N sensor nodes, and sensor nodes are deployed randomly in the sensing field. As shown in Fig. 1, the base station splits the network into clusters and elects some sensor nodes as

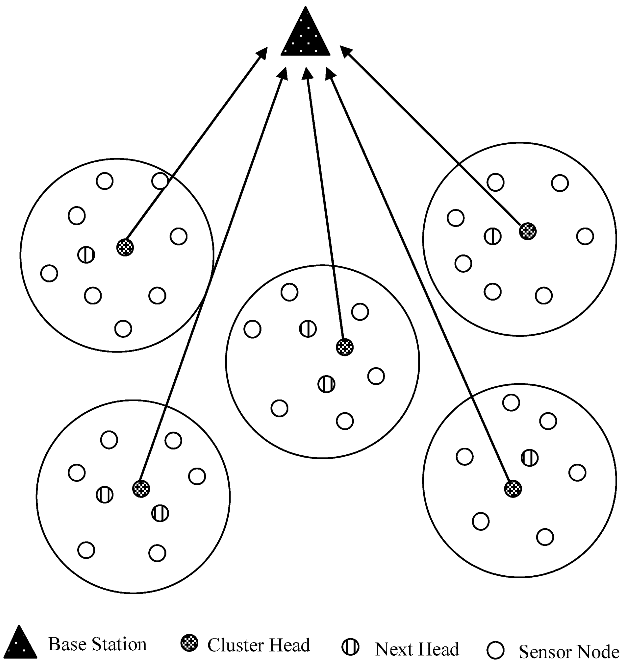


Fig. 1. Cluster topology.

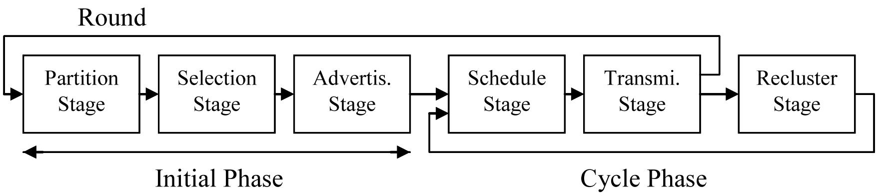


Fig. 2. ADRP operations.

cluster heads, which collect sensor data from other nodes in the clusters and transfer the aggregated data to the base station. Each cluster has one cluster head, next heads and set of sensor nodes. Since data transfers to the base station dissipate much energy, the nodes take turns with the transmission by rotating the cluster heads, which leads to balanced energy consumption of all nodes and hence to a longer lifetime of the network. In our proposed protocol, we consider the following assumptions:

1. There is a base station located far away from the square sensing field.
2. Each sensor node is assigned a unique identifier (ID).
3. Each sensor node has power control and the ability to transmit data to any other sensor node or directly to the base station.
4. Nodes are immobile.
5. All the sensor nodes are location aware. To get the information, sensor nodes can use GPS or other location detect scheme.

4. ADRP protocol

ADRP is a clustering protocol for wireless sensor networks. It is used to collect data from distributed sensor nodes and transmit data to a base station. ADRP is designed to support periodic remote monitoring sensor networks.

A wireless sensor network usually contains a large number of sensor nodes in a wide area, and the base station far from the sensor nodes. Dividing the entire network into clusters would reduce the energy consumed for data communications. The network activity is organized into rounds, where each round has two phases: initial phase and cycle phase, as shown in Fig. 2. The duration of the cycle phase is longer than the duration of the initial phase in order to minimize overhead.

During the initial phase, each node sends its energy status and location to the base station. The base station splits the network into clusters and selects a cluster head for each cluster according to the location information of sensor nodes.

Once the clusters are formed, the base station selects a set of sensor nodes as next heads used during re-cluster stage. The base station sends advertisement message to all the nodes in the network which contains the cluster head ID and next heads for each sensor node.

During the cycle phase, each cluster head creates and distributes the TDMA schedule, which specifies the time slots allocated for each member of the cluster. The cluster head advertises the schedule to its cluster members through broadcasting. Each node is assigned a unique time slot during which it can transmit its data to the cluster head. Upon receiving data packets from its cluster nodes, the cluster head aggregates the data before sending them to the base station. At end of this phase each node selects next head as new cluster head and switch to it. The nodes join the next cluster head and become cluster members in order to complete clusters forming. The old cluster heads switch their status to member nodes and join the next heads.

5. ADRP algorithm details

5.1. Initial phase

Base station receives information about current locations and remaining energy levels from sensor nodes. The base station uses the remaining energy level and locations to split the network into clusters and determine the cluster heads. Once the clusters are formed, the base station determines the next heads. In order to do this, the base station computes the average energy for each cluster in the network, and sensor nodes that have energy storage below this average cannot become next heads for this round.

Once the cluster heads and next heads are determined, the base station broadcast the information including cluster heads and next heads to all sensor nodes. The initial phase consists of three stages: partition stage, selection stage and advertisement stage.

5.1.1. Partition stage

During this stage, each sensor node transmits the data of its position and the amount of energy to the base station. The sensor nodes get their current location by using a global positioning system receiver that is activated at the beginning of each initial phase.

On receiving the data, the base station calculates the energy value of all sensor nodes and then elects the cluster heads by minimizing the total sum of the distances between the cluster heads and sensor nodes. Furthermore, base station makes sure that only nodes with enough energy are participating in the cluster heads selection. ADRP can distribute the energy between the sensor nodes by positioning cluster heads into the centre of clusters. At end of this stage, ADRP partitions the nodes into set of clusters and each cluster is managed by a selected cluster head. There are three different kinds of sensors: Cluster head, Sensor node and Next head. The next stage elects the next head nodes.

5.1.2. Selection stage

Cluster head is responsible for receiving all the data from nodes within the cluster, aggregating this data and send the aggregate data to the base station. If this role was fixed, the cluster head would quickly drain its limited energy and die. Therefore, ADRP includes rotation of this role among all the sensor nodes in the network to distribute the energy load.

In this stage, ADRP protocol requires a set of sensor nodes to be elected as next heads. During cycle phase the sensor nodes can switch from current cluster head to next head.

Once the clusters have been formed, the ADRP selects set of sensor nodes as next heads. To do this, the ADRP computes the threshold (average energy) for each cluster, and whichever nodes have energy below this threshold cannot be next heads for the current round.

The ADRP repeats the following two steps for each cluster to select set of sensor nodes as next head.

1. ADRP computes the threshold for each cluster j

$$Tj = \frac{1}{m}\sum_{i=1}^{m} Ei(t), \tag{2}$$

   where m is number of sensor nodes in cluster j.
   $Ei(t)$ is the current energy of node i. The sensor nodes with higher energy are more likely to become next heads.
2. If current energy of node i greater than or equal to Tj, the threshold of cluster j, then node i is member of set NHj.

$$Ei(t) \geqslant Tj, \quad i \in NHj. \tag{3}$$

Where NHj is the set of nodes that are eligible to be next heads in cluster j.

Once NHj sets have been created, the ADRP elects group of next heads from the sets and specifies its member nodes.

At end of this stage, there are three different kinds of sensors:

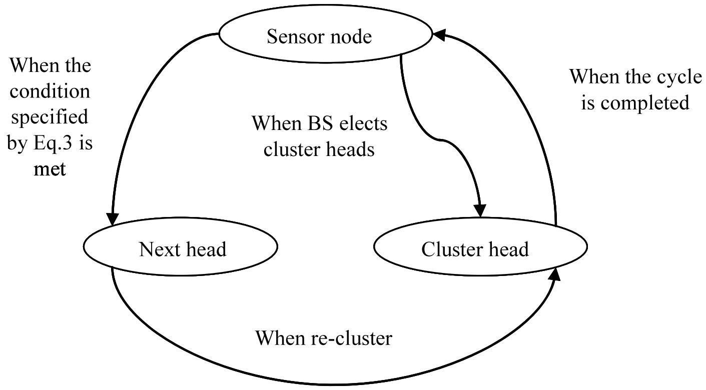


Fig. 3. State transition diagram of node.

1. Cluster heads collect sensor data from cluster members, aggregate the data and forward it to the base station.
2. Sensor nodes gather sensor data and forward the data to the cluster head.
3. Next heads act as sensor nodes but during the re-cluster stage each sensor node selects next head as new cluster head and switch to it.

Fig. 3 shows state transition diagram of sensor node.

5.1.3. Advertisement stage

During this stage, the base station sends a message containing the cluster head ID and next heads for each sensor node. If a node's cluster head ID matches its own ID, the node is a cluster head; otherwise, the node is a sensor node.

5.2. Cycle phase

Cluster head creates and distributes the TDMA schedule, which specifies the time slots allocated for each member of the cluster. Each sensor node sends its data during its allocated transmission time slot. Upon receiving data packets from its cluster nodes, the cluster head aggregates the data before sending them to the base station. At the end of this phase each node selects next head as new cluster head and switch to it. The old cluster head switches its role with the next head. From this point, the old cluster head becomes a normal member. The cycle phase consists of three stages: schedule stage, transmission stage and re-cluster stage.

5.2.1. Schedule stage

Once clusters have been formed, the sensor nodes must send their data to the cluster head. ADRP uses TDMA, which allows the sensor nodes to enter a sleep mode when they are not transmitting data to the cluster head. Also, using a TDMA approach in intra cluster communication ensures there are no collisions of data within the cluster.

Based on the number of nodes in the cluster, the cluster head node creates a TDMA schedule telling each node when it can transmit. The TDMA schedule divides time into a set of slots, the number of slots being equal to the number of nodes in the cluster. Each node is assigned a unique time slot during which it can transmit its data to the cluster head.

5.2.2. Transmission stage

The data transmission stage consists of three major activities:

- Data gathering.
- Data aggregation.
- Data sending.

At each sensing period, all sensor nodes send their data to their cluster heads when cluster heads receive data from member nodes, instead of forwarding all the data, cluster heads check the contents of incoming data and then combine them by eliminating redundant data. Then, the cluster heads transmit the aggregate data to the base station using a CSMA MAC protocol. The data aggregation is to minimize traffic load by eliminating redundancy.

5.2.3. Re-cluster stage

The ADRP periodically re-clusters the network in order to distribute the energy consumption among all sensor nodes in a wireless sensor network.

In the initial phase the base station sends messages containing the cluster head ID and next heads for each sensor node in the network. So, the sensor nodes can switch directly to the next heads without communicate with the base station. Thus, the ADRP protocol forms new clusters each cycle phase.

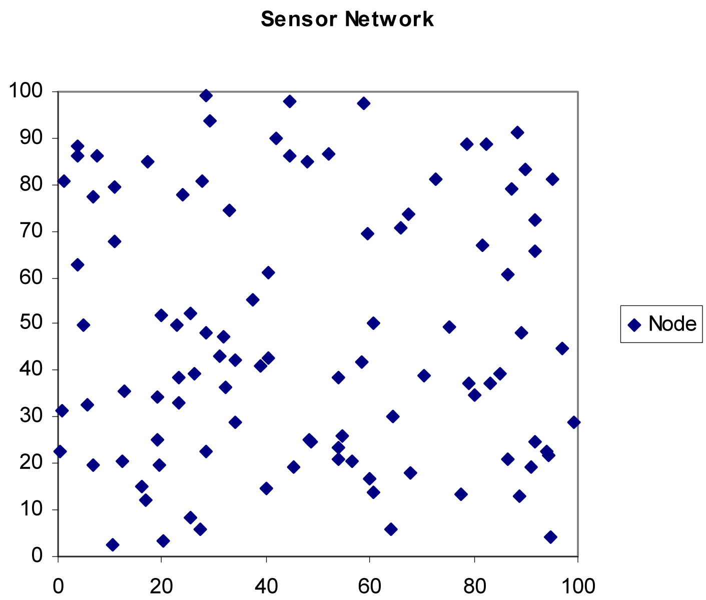


Fig. 4. Random deployment of sensor network in the field.

Table 1
Simulation parameters

Parameter	Value
Network size	100 × 100
Number of nodes	100
Base station location	50 × 175
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
Initial energy	1 Joule
Data packet size	500 bytes
Info packet size	25 bytes

During re-cluster stage, the sensor nodes select next heads to act as cluster heads in next cycle and switch to them. When all sensor nodes in the network select next heads and switch to them, the re-cluster stage is complete and the schedule stage can begin. If there is no next head available, the initial phase can begin.

6. Simulation and discussion

In this section, we analyze the performance of ADRP, simulated using OMNET++ simulator [7], against Low-Energy Adaptive Clustering Hierarchy (LEACH-C) in terms the following metrics:

1. Network lifetime: this metric shows the number of sensor nodes that die over the time of operation.
2. Received data messages: this metric shows the number of data messages successfully delivered to the base station.
3. Energy dissipation: this metric shows the energy consumption over time of activity.
4. Communication overhead: this metric shows the number of messages received at the base station during initial phase to setup the clusters.

6.1. Simulation setup

As shown in Fig. 4, the simulations were configured as network size of 100 × 100 meters with 100 nodes randomly distributed and the base station located at position 50, 175. We have used the same radio as Heinzelman et al. [1,4].

To compute energy consumption for each sending and receiving, we use radio model as describe in [4]. The energy used to send n-bit data a distance d for each sensor node is

$$E_{Tx}(n,d) = nE_{elec} + n\varepsilon_{fs}d^2. \tag{4}$$

The energy used to receive n-bit data a distance d for each sensor node is

$$E_{Rx}(n) = nE_{elec}. \tag{5}$$

The energy for data aggregation is

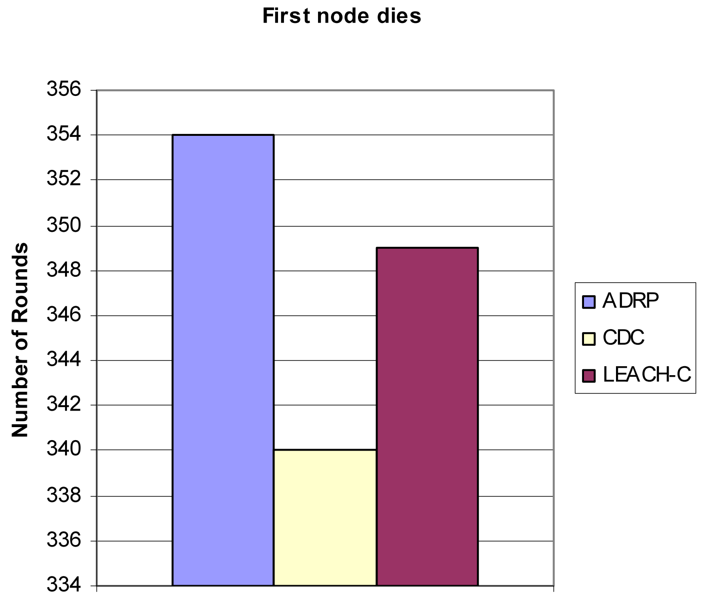
$$E_{DA} = 5 \text{ nJ/bit/signal}, \tag{6}$$

where E_{elec} is the electronics energy, and ε_{fs} is power loss of free space. Table 1 summarizes parameters used in our simulation.

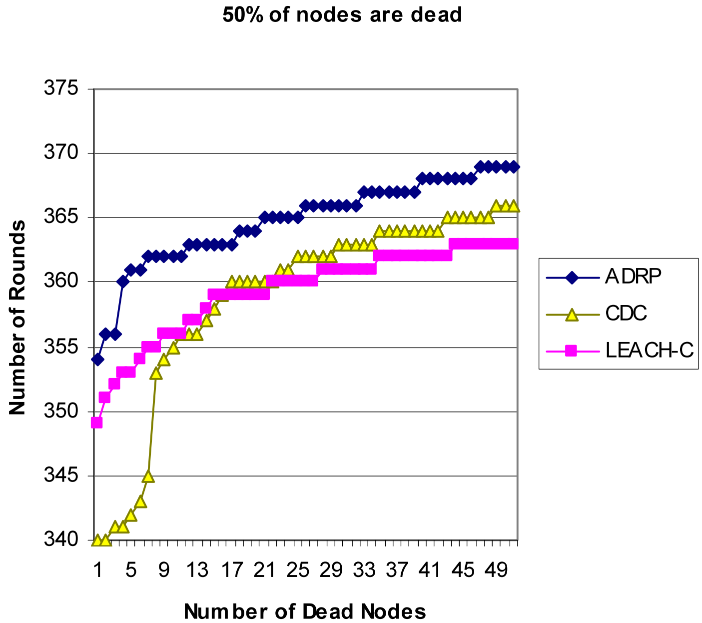
6.2. Simulation results

6.2.1. Network lifetime

We analyze the network life time which is defined by using three metrics FD (First Node Dies), HD (Half of the Nodes Alive), and LD (Last Node Dies) [14]. Since more than one node is necessary to perform the clustering algorithm. The LD represents overall lifetime of wireless sensor network when 80% of sensor nodes die.

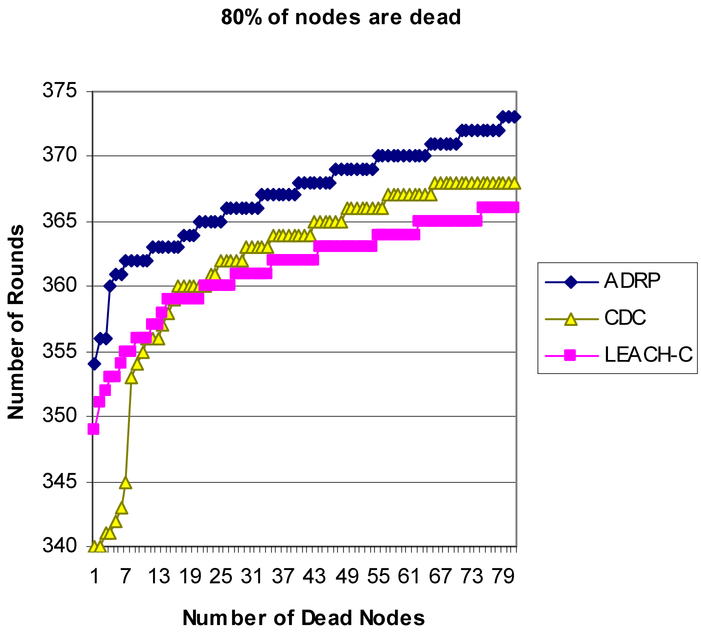


(a)



(b)

Fig. 5. Network lifetime.



(c)

Fig. 5. (*continued*)

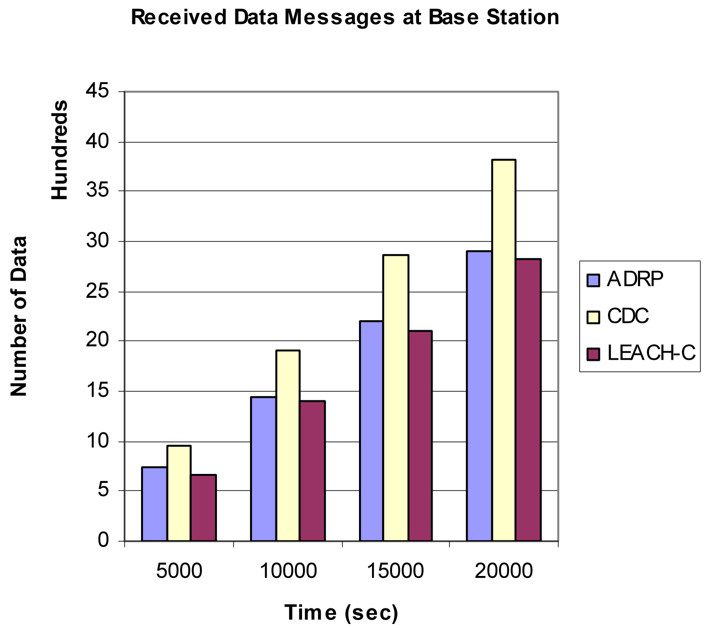
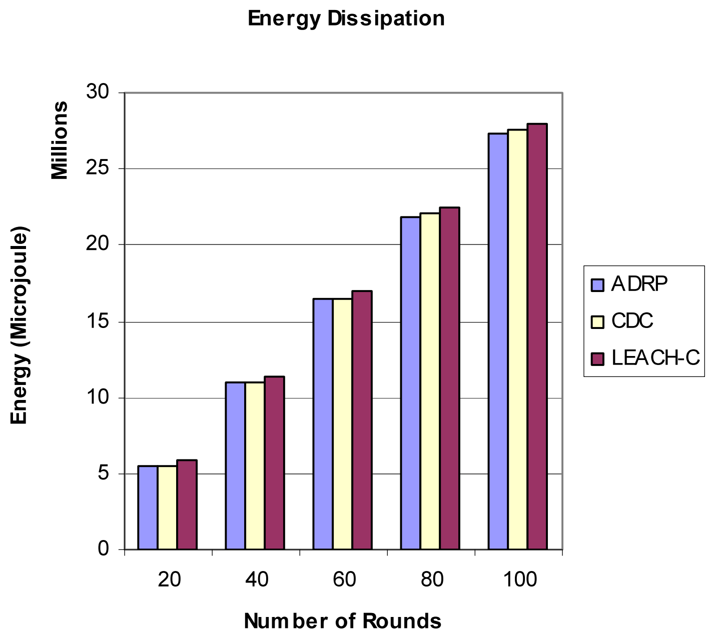


Fig. 6. Number of data messages received by base station.

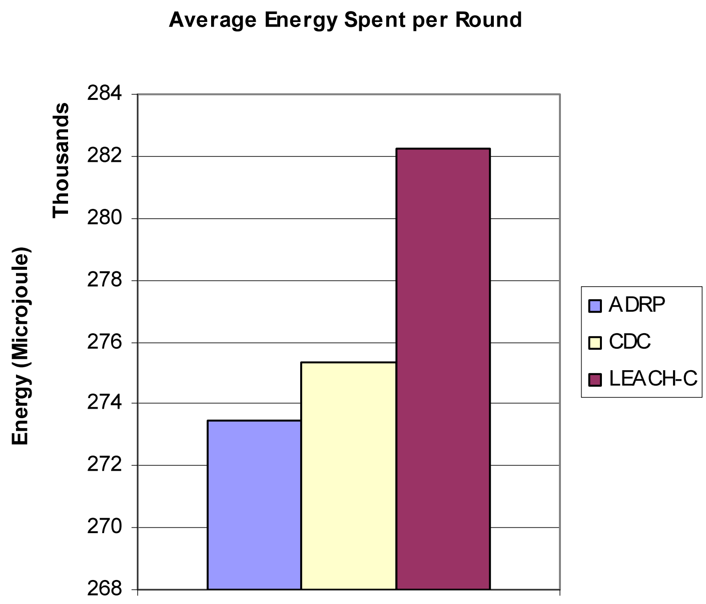
Fig. 5(a) shows the first dead node in LEACH-C and CDC appears earlier than ADRP because the sensor nodes in LEACH-C need to send the status to the base station each round while in ADRP the sensor nodes can switch directly to the next heads without communicate with the base station. In CDC, the role of the cluster head is rotated among the nodes inside the cluster. In such a case, some sensor nodes consume more energy due to the cluster heads are not in the center of clusters. Figs. 5(b), 5(c) show the nodes with ADRP protocol remain alive for longer time than that of using LEACH-C or CDC. ADRP protocol performs much better than LEACH-C and CDC in prolonging the network lifetime for all metrics.

6.2.2. Received data messages

We analyze the number of data messages received by the base station. Fig. 6 shows the number of data messages received by the base station over the time of operation. In ADRP, CDC and LEACH-C, each message is transmitted over



(a)



(b)

Fig. 7. Energy dissipation.

a single hop, to the cluster head, where data aggregation occurs. The aggregate data is sent to the base station, greatly reducing the amount of data transmitted. As the sensor nodes death rate in ADRP (Fig. 5) is less than that in LEACH-C, more data messages will be sent to the base station comparing with LEACH-C. In CDC, the clusters are fixed until node dies. Thus, the latency in data delivery is minimized.

6.2.3. Energy dissipation

Figs. 7(a) and 7(b) show the energy dissipation of the protocols over the time of operation. LEACH-C consumes more energy because the sensor nodes have to communicate with the base station each round to form the clusters while sensor nodes in ADRP can join next heads without communicate with the base station. In CDC, the clusters are fixed until node dies.

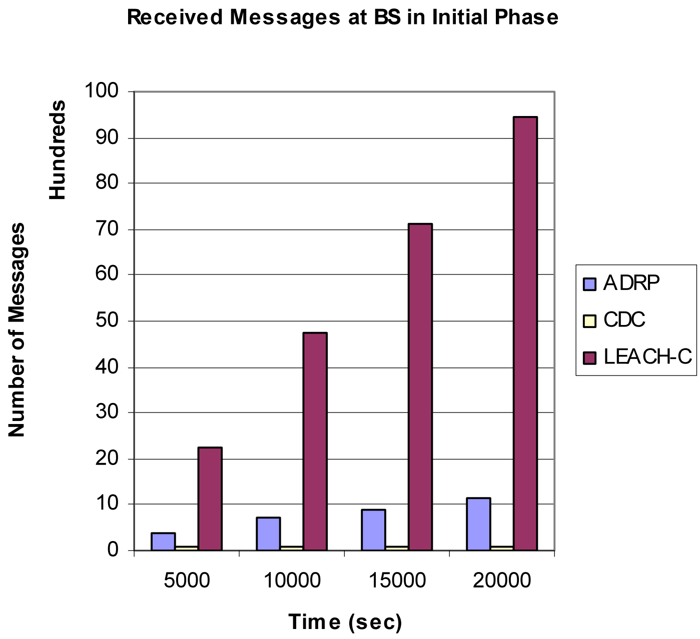


Fig. 8. Communication overhead.

6.2.4. Communication overhead

In ADRP the base station sends a message containing the cluster head ID and next heads for each sensor node in the network. During re-cluster stage, the sensor nodes can switch directly to next heads without communicate with the base station. Thus, it reduces a large number of communication overheads. In CDC, the clusters are fixed until node dies. Fig. 8 shows that the number of messages in initial phase increases gradually in ADRP and CDC, while in LEACH-C the number of messages increases vary fast.

6.3. Simulation summary

Simulation indicates that the ADRP protocol performs much better than LEACH-C and CDC in prolonging the network lifetime for three metrics First Node Dies, Half of the Nodes Alive, and Last Node Dies. As the sensor nodes death rate in ADRP is less than that in LEACH-C, more data messages will be sent to the base station comparing with LEACH-C. In CDC, the clusters are fixed until node dies. Thus, the latency in data delivery is minimized.

In ADRP protocol the sensor nodes can switch directly to next heads without communicate with the base station. Thus, it reduces a large number of communication overheads and consumes the least amount of sensor energy.

7. Conclusion and future work

We introduce an adaptive clustering scheme ADRP, for electing cluster heads and next heads in wireless sensor networks. The selection of cluster heads and next heads are weighted by the remaining energy of sensor nodes and the average energy of each cluster. The sensor nodes with the highest energy in the clusters can be a cluster heads at different cycles of time. By means of the former, the role of cluster heads can be switched dynamically.

Simulations results show that ADRP has extended the lifetime of the network and reduced the communication overhead. Hence, the performance of the proposed protocol is better in terms of lifetime, data delivery and communication overhead, when compared with LEACH-C and CDC.

When the sensor nodes use single hop communication to reach the base station, the sensor nodes located farther away from the base station have the highest energy load due to long range communication. When the sensor nodes use multi-hop communication to reach the base station, the sensor nodes closer to the base station have a higher load of relaying packets. As for future work, we will design an adaptive and energy efficient protocol to determine the optimum mode of communication in each cluster single hop or multihop.

References

[1] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy efficient communication protocol for wireless sensor networks, in: Proceedings of the 33rd Hawaii International Conference on System Science, vol. 2, 2000.

[2] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, A Survey on sensor networks, IEEE Commun. Mag. 40 (8) (2002) 102–114.

[3] T. Voigt, H. Ritter, J. Schiller, Solar-aware routing in wireless sensor networks, in: Ninth IEEE Symposium on Computers and Communications vol. 1, 2004, pp. 238–243.
[4] W.B. Heinzelman, A. Chandrakasan, H. Balakrishnan, An application-specific protocol architecture for wireless microsensor networks, IEEE Trans. Wireless Commun. 1 (4) (2002) 660–670.
[5] J. Al-Karaki, A. Kamal, Routing techniques in wireless sensor networks: a survey, IEEE Wireless Commun. 11 (6) (2004) 6–28.
[6] S.D. Muruganathan, D.C.F. Ma, R.I. Bhasin, A.O. Fapojuwo, A centralized energy-efficient routing protocol for wireless sensor networks, IEEE Radio Commun. 43 (3) (2005) S8–13.
[7] OMNET++ Simulation Environment, http://www.omnetpp.org.
[8] S. Lindsey, C. Raghavendra, PEGASIS: power-efficient gathering in sensor information systems, in: IEEE Aerospace Conference Proceedings, vol. 3, 2002, pp. 1125–1130.
[9] A. Manjeshwar, D.P. Agarwal, TEEN: a routing protocol for enhanced efficiency in wireless sensor networks, in: 15th International Parallel and Distributed Processing Symposium (IPDPS'01), vol. 3, 2001.
[10] A. Manjeshwar, D.P. Agarwal, APTEEN: a hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks, in: Proceedings of the 16th International Parallel and Distributed Processing Symposium, 2002, pp. 195–202.
[11] D. Culler, D. Estrin, M. Srivastava, Overview of sensor networks, IEEE Computer 37 (8) (2004) 41–49.
[12] N. Israr, I. Awan, Multihop clustering algorithm for load balancing in wireless sensor networks, Internat. J. Simul. Systems Sci. Technol. 8 (1) (2007) 13–25.
[13] V. Raghunathan, et al., Energy-aware wireless microsensor networks, IEEE Signal Process. Mag. 1 (2) (2002) 40–50.
[14] M.J. Handy, M. Haase, D. Timmermann, Low energy adaptive clustering hierarchy with deterministic cluster-head selection, in: Proceedings 4th International Workshop on Mobile and Wireless Communications Network, 2002, pp. 368–372.
[15] K. Akkaya, M. Younis, A survey on routing protocols for wireless sensor networks, Elsevier Journal of Ad Hoc Networks 3 (3) (2005) 325–349.
[16] O. Younis, S. Fahmy, Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks, IEEE Trans. Mobile Comput. 23 (4) (2004) 366–379.
[17] A. Abbasi, M. Younis, A survey on clustering algorithms for wireless sensor networks, Elsevier J. Computer Commun. 30 (2007) 2826–2841.
[18] F. Bajaber, I. Awan, Centralized dynamic clustering for wireless sensor network, in: International Conference on Advanced Information Networking and Applications Workshops, 2009, pp. 193–198.