A Centralized Energy-Efficient Routing Protocol for Wireless Sensor Networks

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Abstract

Wireless sensor networks consist of small battery powered devices with limited energy resources. Once deployed, the small sensor nodes are usually inaccessible to the user, and thus replacement of the energy source is not feasible. Hence, energy efficiency is a key design issue that needs to be enhanced in order to improve the life span of the network. Several network layer protocols have been proposed to improve the effective lifetime of a network with a limited energy supply. In this article we propose a centralized routing protocol called Base-Station Controlled Dynamic Clustering Protocol (BCDCP), which distributes the energy dissipation evenly among all sensor nodes to improve network lifetime and average energy savings. The performance of BCDCP is then compared to clustering-based schemes such as Low-Energy Adaptive Clustering Hierarchy (LEACH), LEACH-centralized (LEACH-C), and Power-Efficient Gathering in Sensor Information Systems (PEGASIS). Simulation results show that BCDCP reduces overall energy consumption and improves network lifetime over its comparatives.

Introduction

Wireless sensor networks consist of hundreds to thousands of low-power multifunctioning sensor nodes, operating in an unattended environment, with limited computational and sensing capabilities. Recent developments in low-power wireless integrated microsensor technologies have made these sensor nodes available in large numbers, at a low cost, to be employed in a wide range of applications in military and national security, environmental monitoring, and many other fields [1]. In contrast to traditional sensors, sensor networks offer a flexible proposition in terms of the ease of deployment and multiple functionalities. In classical sensors, the placement of the nodes and the network topology need to be predetermined and carefully engineered. However, in the case of modern wireless sensor nodes, their compact physical dimensions permit a large number of sensor nodes to be randomly deployed in inaccessible terrains. In addition, the nodes in a wireless sensor network are also capable of performing other functions such as data processing and routing, whereas in traditional sensor networks special nodes with computational capabilities have to be installed separately to achieve such functionalities.

In order to take advantage of these features of wireless sensor nodes, we need to account for certain constraints associated with them. In particular, minimizing energy consumption is a key requirement in the design of sensor network protocols and algorithms. Since the sensor nodes are equipped with small, often irreplaceable, batteries with limited power capacity, it is essential that the network be energy efficient in order to maximize the life span of the network [1, 2]. In addition to this, wireless sensor network design also demands other requirements such as fault tolerance, scalability, production costs, and reliability. It is therefore critical that the designer takes these factors into account when designing protocols and algorithms for wireless sensor networks [1].

Since a large number of low-power nodes have to be networked together, conventional techniques such as direct transmissions from any specified node to a distant base station have to be avoided. In the direct transmission protocol, the base station serves as the destination node to all the other nodes in the network where the end user can access the sensed data. When a sensor node transmits data directly to the base station, the energy loss incurred can be quite extensive depending on the location of the sensor nodes relative to the base station. In such a scenario, the nodes that are farther away from the base station will have their power sources drained much faster than those nodes that are closer to the base station [3]. On the other hand, utilizing a conventional multihop routing scheme such as the Minimum Transmission Energy (MTE) routing protocol will also result in an equally undesirable effect. In MTE, the nodes closest to the base station will rapidly drain their energy resources since these nodes engage in the routing of a large number of data messages (on behalf of other nodes) to the base station [2, 3].

Various routing protocols have been proposed for wireless sensor networks to alleviate such problems. Data-centric routing is a commonly utilized approach that uses attribute-based addressing to perform the collective sensing task. In data-centric routing, sensor nodes are assigned tasks based on interest disseminations that originate from another node in the network [1]. The Sensor Protocols for Information via Negotiation (SPIN) [4] protocol family and directed diffusion [5] are two network layer protocols based on data-centric routing. In SPIN, the sensor nodes that have data to send broadcast an advertisement to their neighbors and send the actual data only to those nodes that are interested. To reduce the energy expended in the broadcast of advertisements, the SPIN protocol family uses meta-data descriptors, which describe the actual sensor data in a more compact size. The directed diffusion paradigm, however, uses a slightly different type of data-centric routing. In this scheme, the sink broadcasts the interests to all sensor nodes in the network. Each sensor node stores the interest in a local cache, and uses the gradient fields within the interest descriptors to identify the most suitable path to the sink [5]. These paths are then used by source nodes to communicate the sensed data to the sink.

Although the data-centric routing approach provides a reliable and robust solution to wireless sensor networks, there are still some shortcomings associated with protocols utilizing this technique. In the worst case, both SPIN and directed diffusion suffer from the amount of overhead energy spent in activities such as advertising, requesting, and gradient setup. Furthermore, the excessive time spent in such activities might not suit some applications that require the sensor nodes to respond quickly to an emergency situation. A more apt solution for

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such scenarios is a clustering-based protocol. In the clustered routing approach, nodes are grouped into clusters, and a dedicated cluster head node collects, processes, and forwards the data from all the sensor nodes within its cluster. The application of a clustering-based approach helps reduce the amount of information that needs to be transmitted by performing data aggregation at the cluster heads before forwarding the data to the end user. Other key advantages gained through utilizing clustered routing are bandwidth reusability, enhanced resource allocation, and improved power control [2].

However, the application of conventional clustering to wireless sensor networks does not improve network lifetime since the conventional clustering scheme assumes the cluster heads to be fixed, and thus requires them to be high-energy nodes. To alleviate this deficiency, an adaptive clustering scheme called Low-Energy Adaptive Clustering Hierarchy (LEACH) is proposed in [3] that employs the technique of randomly rotating the role of a cluster head among all the nodes in the network. The operation of LEACH is organized in rounds where each round consists of a setup phase and a transmission phase. During the setup phase, the nodes organize themselves into clusters with one node serving as the cluster head in each cluster. The decision to become a cluster head is made locally within each node, and a predetermined percentage of the nodes serve as local cluster heads in each round, on average. During the transmission phase, the self-elected cluster heads collect data from nodes within their respective clusters and apply data fusion before forwarding them directly to the base station. At the end of a given round, a new set of nodes becomes cluster heads for the subsequent round. Furthermore, the duration of the transmission phase is set much larger than that of the setup phase in order to offset the overhead due to cluster formation. Thus, LEACH provides a good model where localized algorithms and data aggregation can be performed within randomly self-elected cluster heads, which help reduce information overload and provide a reliable set of data to the end user. It has been shown that LEACH provides significant energy savings and prolonged network lifetime over fixed clustering and other conventional schemes discussed above [3].

A centralized version of LEACH, LEACH-C, is proposed in [2]. Unlike LEACH, where nodes self-configure themselves into clusters, LEACH-C utilizes the base station for cluster formation. During the setup phase of LEACH-C, the base station receives information regarding the location and energy level of each node in the network. Using this information, the base station finds a predetermined number of cluster heads and configures the network into clusters. The cluster groupings are chosen to minimize the energy required for non-cluster-head nodes to transmit their data to their respective cluster heads. Although the other operations of LEACH-C are identical to those of LEACH, results presented in [2] indicate a definite improvement over LEACH. The authors of [2] cite two key reasons for the improvement:

- The base station utilizes its global knowledge of the network to produce better clusters that require less energy for data transmission.
- The number of cluster heads in each round of LEACH-C equals a predetermined optimal value, whereas for LEACH the number of cluster heads varies from round to round due to the lack of global coordination among nodes.

Power Efficient Gathering in Sensor Information Systems (PEGASIS), another clustering-based routing protocol, further enhances network lifetime by increasing local collaboration among sensor nodes [6]. In PEGASIS, nodes are organized into a chain using a greedy algorithm so that each node transmits to and receives from only one of its neighbors. In each round, a randomly chosen node from the chain will transmit the aggregated data to the base station, thus reducing the per round energy expenditure compared to LEACH.

In this article we propose another clustering-based routing protocol called Base Station Controlled Dynamic Clustering Protocol (BCDCP), which utilizes a high-energy base station to set up clusters and routing paths, perform randomized rotation of cluster heads, and carry out other energy-intensive tasks. The key ideas in BCDCP are the formation of balanced clusters where each cluster head serves an approximately equal number of member nodes to avoid cluster head overload, uniform placement of cluster heads throughout the whole sensor field, and utilization of cluster-head-to-cluster-head (CH-to-CH) routing to transfer the data to the base station. As shown below, BCDCP yields an improved system lifetime and better energy savings over the abovementioned clustering-based routing protocols. The rest of the article is organized in the following form. We outline the network and radio models assumed in BCDCP. A detailed description of BCDCP is presented, followed by simulated performance results. Finally, we present our conclusion.

Network and Radio Models

The Network Model and Architecture

As mentioned above, the foundation of BCDCP lies in the realization that the base station is a high-energy node with a large amount of energy supply. Thus, BCDCP utilizes the base station to control the coordinated sensing task performed by the sensor nodes. In this article we assume a sensor network model, similar to those used in [3, 6], with the following properties:

- A fixed base station is located far away from the sensor nodes.
- The sensor nodes are energy constrained with a uniform initial energy allocation.
- The nodes are equipped with power control capabilities to vary their transmitted power.
- Each node senses the environment at a fixed rate and always has data to send to the base station.
- All sensor nodes are immobile.

The two key elements considered in the design of BCDCP are the sensor nodes and base station. The sensor nodes are geographically grouped into clusters and capable of operating in two basic modes:

- The cluster head mode
- The sensing mode

In the sensing mode, the nodes perform sensing tasks and transmit the sensed data to the cluster head. In cluster head mode, a node gathers data from the other nodes within its cluster, performs data fusion, and routes the data to the base station through other cluster head nodes. The base station in turn performs the key tasks of cluster formation, randomized cluster head selection, and CH-to-CH routing path construction.

The Radio Model

As shown in Fig. 1, a typical sensor node consists of four major components: a data processor unit; a micro-sensor; a radio communication subsystem that consists of transmitter/receiver electronics, antennae, and an amplifier; and a power supply unit [7]. Although energy is dissipated in all of the first three components of a sensor node, we mainly consider the energy dissipations associated with the radio component since the core objective of this article is to develop an energy-efficient network layer protocol to improve network lifetime. In addition, energy dissipated during data aggregation in the cluster head nodes is also taken into account.

In our analysis, we use the same radio model discussed in [2]. The transmit and receive energy costs for the transfer of a k-bit data message between two nodes separated by a distance of r meters is given by Eqs. 1 and 2, respectively.

$$E_T(k,r) = E_{Tx}\, k + E_{amp}(r)\, k \quad (1)$$

$$E_R(k) = E_{Rx}\, k \quad (2)$$

where $E_T(k,r)$ in Eq. 1 denotes the total energy dissipated in the transmitter of the source node, and $E_R(k)$ in Eq. 2 represents the energy cost incurred in the receiver of the destination node. The parameters E_{Tx} and E_{Rx} in Eqs. 1 and 2 are the per bit energy dissipations for transmission and reception, respectively. $E_{amp}(r)$ is the energy required by the transmit amplifier to maintain an acceptable signal-to-noise ratio in order to transfer data messages reliably. As is the case in [2], we use both the free-space propagation model and the two-ray ground propagation model to approximate the path loss sustained due to wireless channel transmission. Given a threshold transmission distance of r_o, the free-space model is employed when $r \le r_o$, and the two-ray model is applied for cases where $r > r_o$. Using these two models, the energy required by the transmit amplifier $E_{amp}(r)$ is given by

$$E_{amp}(r) = \begin{cases} \varepsilon_{FS} r^4, & r \le r_o \\ \varepsilon_{TR} r^4, & r > r_o \end{cases} \quad (3)$$

where ε_{FS} and ε_{TR} denote transmit amplifier parameters corresponding to the free-space and the two-ray models, respectively, and r_o is the threshold distance given by

$$r_o = \sqrt{\varepsilon_{FS} / \varepsilon_{TR}}. \quad (4)$$

We assumed the same set of parameters used in [2] for all experiments throughout the article: $E_{Tx} = E_{Rx} = 50$ nJ/bit, $\varepsilon_{FS} = 10$ pJ/b/m^2, and $\varepsilon_{TR} = 0.0013$ pJ/b/m^4. Moreover, the energy cost for data aggregation is set as $E_{DA} = 5$ nJ/b/message.

Base Station Controlled Dynamic Clustering Protocol

BCDCP is a wireless sensor routing protocol with the base station being an essential component with complex computational abilities, thus making the sensor nodes very simple and cost effective. BCDCP operates in two major phases: setup and data communication. In this section we describe the details of the two phases. As a prelude, we first provide details of the addressing scheme used to identify the sensor nodes.

The Addressing Scheme

In traditional networks, nodes are assigned fixed addresses. However, due to the high costs associated with assigning and maintaining these types of addresses, the fixed addressing scheme might not be suitable for wireless sensor networks [8]. In addition, since the end user of a wireless sensor network is more interested in attribute-based queries such as "Send me the number of cars parked in lot number 7," it is more apt to use an addressing scheme based on the nodes' attributes and geographical positions [1, 8]. Therefore, for BCDCP we use a class-based addressing of the form <Location ID, Node Type ID>. The Location ID identifies the location of a node that conducts sensing activities in a specified region of the network. It is assumed that the base station keeps up-to-date information on the location of all the nodes in the network. Each node within the cluster is further provided with a Node Type ID that describes the functionality of the sensor such as seismic sensing, thermal sensing, and so on.

The Setup Phase

The main activities in this phase are cluster setup, cluster head selection, CH-to-CH routing path formation, and schedule creation for each cluster. During each setup phase, the base station receives information on the current energy status from all the nodes in the network. Based on this feedback, the base station first computes the average energy level of all the nodes, and then chooses a set of nodes, denoted $\mathbb{S}$, whose energy levels are above the average value. Cluster heads for the current round will be chosen from the set $\mathbb{S}$, which ensures that only nodes with sufficient energy get selected as cluster heads, while those with low energy can prolong their lifetime by performing tasks that require low energy costs. The next major tasks for the base station are:

- To identify N_{CH} cluster head nodes from the chosen set (i.e., {cluster head nodes} $\in \mathbb{S}$)
- To group the other nodes into clusters such that the overall energy consumption during the data communication phase is minimized

In BCDCP, we accomplish these tasks by means of an iterative cluster splitting algorithm. This simple algorithm first splits the network into two subclusters, and proceeds further by splitting the subclusters into smaller clusters. The base station repeats the cluster splitting process until the desired number of clusters N_{CH} is attained. The iterative cluster splitting algorithm ensures that the selected cluster heads are uniformly placed throughout the whole sensor field by maximizing the distance between cluster heads in each splitting step. Furthermore, in order to evenly distribute the load on all cluster heads, we utilize the balanced clustering technique [9] where each cluster is split so that the resulting subclusters have approximately the same number of sensor nodes. Accordingly, a single iteration of the cluster splitting algorithm consists of the following four steps:

- **Step 1**: From the set $\mathbb{S}$ which contains all the nodes that are eligible to become cluster heads, choose two nodes, s_1 and s_2, that have the maximum separation distance.
- **Step 2**: Group each of the remaining nodes in the current cluster with either s_1 or s_2, whichever is closest.
- **Step 3**: Balance the two groups so that they have approximately the same number of nodes; this forms the two subclusters.
- **Step 4**: Split $\mathbb{S}$ into smaller sets $\mathbb{S}_1$ and $\mathbb{S}_2$ according to the subcluster groupings performed in step 3.

The second major activity within the setup phase is the formation of routing paths. As discussed earlier, the BCDCP protocol uses a CH-to-CH multihop routing scheme to transfer the sensed data to the base station. Once the clusters and the cluster head nodes have been identified, the base station chooses the lowest-energy routing path and forwards this info to the sensor nodes along with the details on cluster groupings and selected cluster heads. The routing paths are selected by first connecting all the cluster head nodes using the minimum spanning tree approach [10] that minimizes the energy consumption for each cluster head, and then ran-

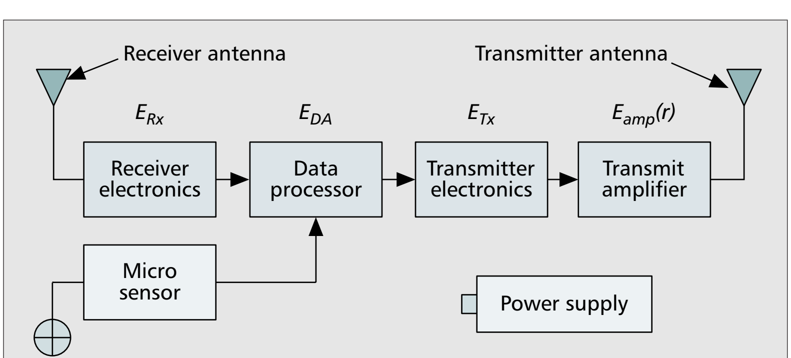

FIGURE 1. *Four major components and associated energy cost parameters of a typical sensor node.*

Cluster head SCID	Time slot 1	Time slot 2	Time slot 3
00	01	10	11
01	00	10	11
10	00	01	11
11	00	01	10

TABLE 1. *The schedule creation scheme used in BCDCP for a cluster with four nodes.*

domly choosing one cluster head node to forward the data to the base station. The random choice of the cluster head that transmits to the base station is justified since data transmission to the base station is an energy-intensive task, and utilizing the cluster head closest to the base station to frequently perform this task will render heavy depletion of energy resources for the nodes closer to the base station. Thus, by randomizing the cluster head transmissions to the base station, BCDCP distributes the burden of routing evenly among all cluster heads.

Schedule creation is the last major issue related to the setup phase. The BCDCP protocol utilizes a time-division multiple access (TDMA) scheduling scheme to minimize collisions between sensor nodes trying to transmit data to the cluster head. After cluster formation, the base station assigns an interim schedule creation ID (SCID) for all the nodes within a cluster. Table 1 demonstrates how this SCID is utilized for scheduling sensor node transmissions to the cluster head for a sample cluster with four nodes. As shown in Table 1, the sensor nodes use the 2-bit SCID to schedule themselves to the appropriate TDMA time slot. For instance, when SCID 00 is assigned to the cluster head, nodes with SCID 01, 10, and 11 transmit their data in time slots 1, 2, and 3, respectively. When the cluster head has an SCID of 01, the transmit order changes slightly, with node 00 transmitting at time slot 1, node 10 at time slot 2, and node 11 at time slot 3, and so on. In general, for a cluster with M nodes, an m-bit schedule creation scheme is used where m represents the smallest integer value greater than or equal to $\log_2 M$.

The Data Communication Phase

The data communication phase consists of three major activities:
- Data gathering
- Data fusion
- Data routing

Using the TDMA schedule creation scheme described above, each sensor node transmits the sensed information to its cluster head. Since sensor nodes are geographically grouped into clusters, these transmissions consume minimal energy due to small spatial separations between the cluster head and the sensing nodes. Once data from all sensor nodes have been received, the cluster head performs data fusion on the collected data, and reduces the amount of raw data that needs to be sent to the base station. The compressed data, along with the information required by the base station to properly identify and decode the cluster data, are then routed back to the base station via the CH-to-CH routing path created by the base station. Besides, we also assume that the fused data from a given cluster head undergoes further processing as it hops along the CH-to-CH routing path.

Another key issue that needs to be addressed here is the radio interference caused by neighboring clusters that could hinder the operation of any given cluster [3]. BCDCP utilizes code-division multiple access (CDMA) codes to counteract this problem. Each cluster is assigned a spreading code that the nodes in the cluster use to distinguish their data transmissions from those of nodes in neighboring clusters. Once the data gathering process is complete, the cluster head uses the same spreading code assigned to the cluster to route data back to the base station.

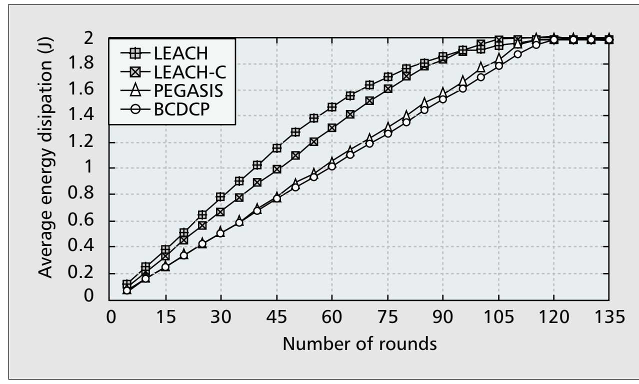

FIGURE 2. *A comparison of BCDCP's average energy dissipation with other clustering-based protocols.*

Performance Evaluation

To assess the performance of BCDCP, we simulated BCDCP performance using Matlab® and compared its performance with other clustering-based routing protocols such as LEACH, LEACH-C, and PEGASIS. Performance is measured by quantitative metrics of average energy dissipation, system lifetime, total data messages successfully delivered, and number of nodes that are alive. Throughout the simulations, we consider several random network configurations with 500 nodes where each node is assigned an initial energy of 2J. Furthermore, the number of data frames transmitted for each round is set at 40; the data message size for all simulations is fixed at 500 bytes, of which 25 bytes represent the length of the packet header.

In the first experiment, we simulate 50 different 100 m × 100 m network topologies with the base station located at least 75 m away from the nearest node. Figure 2 shows the average energy dissipation of the protocols under study over the number of rounds of operation. This plot clearly shows that BCDCP has a much more desirable energy expenditure curve than those of LEACH, LEACH-C, and PEGASIS. On average, BCDCP exhibits a reduction in energy consumption of 40 and 30 percent over LEACH and LEACH-C, respectively. This is because all the cluster heads in both LEACH and LEACH-C transmit data directly to the distant base station, which in turn causes significant energy losses in the cluster head nodes. Both BCDCP and PEGASIS alleviate this problem by having only one cluster head node forward the data to the base station. However, the CH-to-CH routing approach used in BCDCP still outperforms PEGASIS by 5 percent since the utilization of the greedy algorithm in PEGASIS results in a gradual increase in neighbor distances. This in turn increases the communication energy cost for those PEGASIS nodes that have far neighbors [6]. As shown shortly, increasing neighbor distances will have a significant effect on PEGASIS' performance when the area of the sensor field is increased.

The improvement gained through BCDCP is further exemplified by the system lifetime graph in Fig. 3. This plot shows the number of nodes that remain alive over the number of rounds of activity for the 100 m × 100 m network scenario. With BCDCP, all the nodes remain alive for 105 rounds, while the corresponding numbers for LEACH, LEACH-C, and PEGASIS are 40, 65, and 80, respectively. Furthermore, if system lifetime is defined as the number of rounds for which 75 percent of the nodes remain alive, BCDCP exceeds

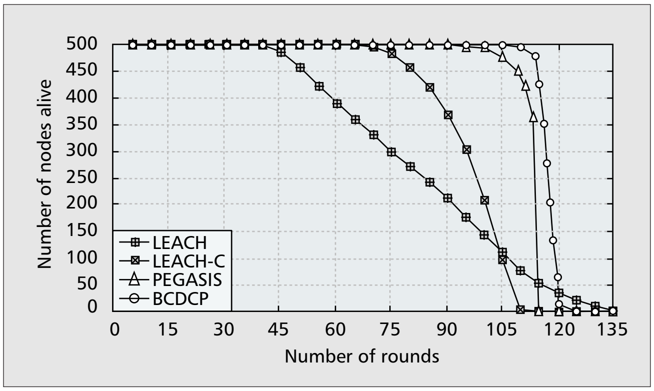

FIGURE 3. *A comparison of BCDCP's system lifetime with other clustering-based protocols.*

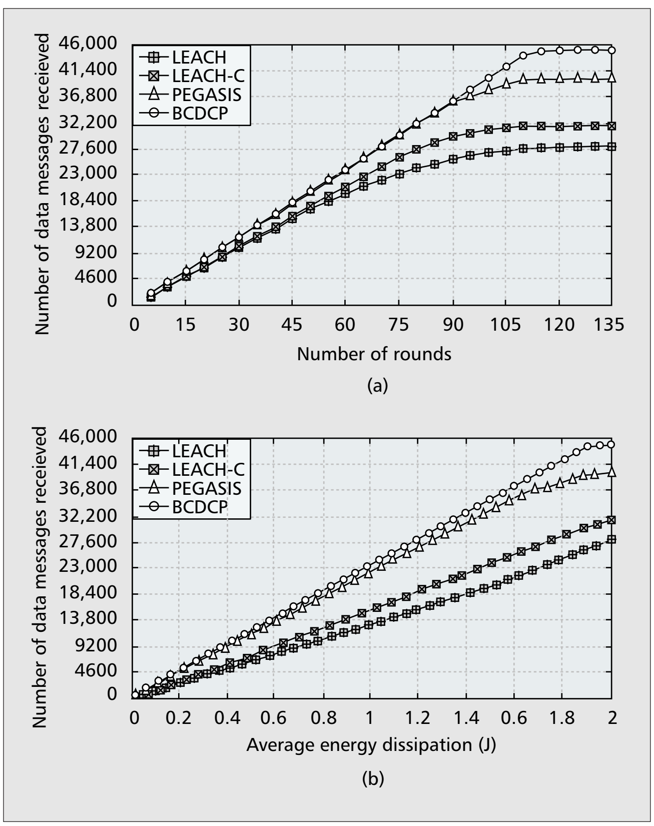

FIGURE 4. *Total number of data messages received at the base station: a) over the number of rounds of operation; b) as a function of average energy dissipation.*

the system lifetime of LEACH by 100 percent and outperforms that of LEACH-C by 30 percent. A 5 percent improvement in system lifetime is observed for BCDCP over PEGASIS. However, this improvement is expected to be more significant for networks with larger dimensions due to the reasons cited above.

Next we analyze the number of data messages received by the base station for the four routing protocols under consideration. For this experiment, we again simulated 50 different 100 m × 100 m network topologies where each node begins with an initial energy of 2J. Figure 4a shows the total number of data messages received by the base station over the number of rounds of activity. The plot clearly illustrates the effectiveness of BCDCP in delivering significantly more data messages than its counterparts. BCDCP offers improvements in data delivery by factors of 60, 40, and 15 percent over LEACH,

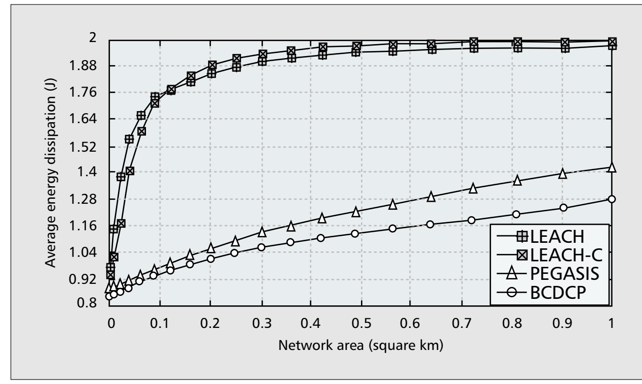

FIGURE 5. *Average energy dissipation over varying network areas.*

LEACH-C, and PEGASIS, respectively. Moreover, results in Fig. 4b confirm that BCDCP delivers the most data messages per unit of energy of the four schemes.

In the final experiment, we evaluate the performance of the routing protocols as the area of the sensor field is increased. For this simulation, 500 nodes are randomly placed in a square field of varying network areas with the base station located at least 100 m away from the closest sensor node, and results were obtained over 25 different network topologies for each network area instance. Figure 5 shows the average energy dissipation of the four protocols, at the end of 50 rounds of activity, as a function of network area. Clearly, BCDCP outperforms both LEACH and LEACH-C as network area increases. This is mainly because the two versions of LEACH do not ensure that the cluster heads are uniformly placed across the whole sensor field. As a result, the cluster head nodes in LEACH and LEACH-C can become concentrated in a certain region of the network, in which case nodes from the "cluster head deprived" regions will dissipate a considerable amount of energy while transmitting their data to a faraway cluster head. BCDCP alleviates this problem by evenly allocating cluster heads across the sensor field during the cluster splitting process. Another factor that helps BCDCP attain better performance over LEACH and LEACH-C is the utilization of the balanced clustering approach. Using balanced clustering, BCDCP distributes the load evenly among the cluster heads, whereas in the cases of LEACH and LEACH-C some cluster heads can be overloaded while others only serve a handful of nodes. Also notable in Fig. 5 is a significant energy saving through utilizing BCDCP over PEGASIS. For a network with area 1 km^2, BCDCP reduces average energy consumption by 11 percent from PEGASIS. As discussed earlier, the degradation in PEGASIS' performance over increasing network area is a result of the gradual increase in neighbor distances while using a greedy algorithm for chain formation. Finally, the plot in Fig. 6 further illustrates the effectiveness of BCDCP for wireless sensor applications that cover a large network area. As shown in Fig. 6, more than 90 percent of the BCDCP nodes still remain alive for a network with area 1 km^2, while the other three protocols encounter significant sensor node deaths. From these analyses, it is clear that BCDCP offers significant performance gain for networks with large coverage areas. However, it is noted that the performance gain of BCDCP over the other clustering-based protocols decreases as the sensor field area becomes small.

Conclusions

In this article we propose a centralized clustering-based routing protocol, BCDCP, that utilizes the high-energy base station to perform most energy-intensive tasks. By using the base station, the sensor nodes are relieved of performing energy-intensive computational tasks such as cluster setup, cluster

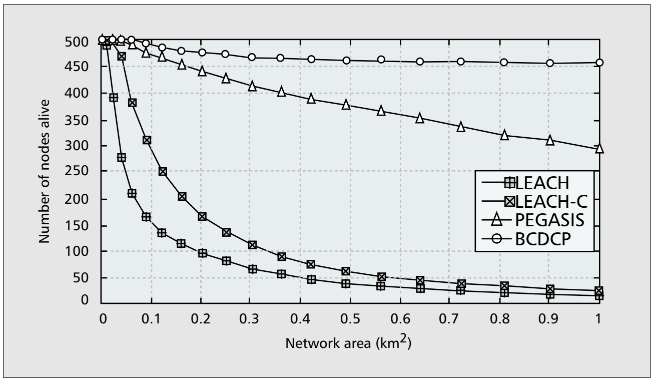

FIGURE 6. *Number of nodes alive as a function of network area.*

head selection, routing path formation, and TDMA schedule creation.

Performance of the proposed BCDCP protocol is assessed by simulation and compared to other clustering-based protocols (LEACH, LEACH-C, and PEGASIS). The simulation results show that BCDCP outperforms its comparatives by uniformly placing cluster heads throughout the whole sensor field, performing balanced clustering, and using a CH-to-CH routing scheme to transfer fused data to the base station. It is also observed that the performance gain of BCDCP over its counterparts increases with the area of the sensor field. Therefore, it is concluded that BCDCP provides an energy-efficient routing scheme suitable for a vast range of sensing applications.

Acknowledgments

This research is supported in part by a grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada and the University of Calgary. The authors thank the anonymous reviewers whose comments have significantly improved the quality of this article.

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