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Increasing network lifetime by balancing node energy consumption in heterogeneous sensor networks

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Summary

Sensor nodes are powered by battery and have severe energy constraints. The typical many-to-one traffic pattern causes uneven energy consumption among sensor nodes, that is, sensor nodes near the base station or a cluster head have much heavier traffic burden and run out of power much faster than other nodes. The uneven node energy dissipation dramatically reduces sensor network lifetime. In a previous work, we presented the chessboard clustering scheme to increase network lifetime by balancing node energy consumption. To achieve good performance and scalability, we propose to form a heterogeneous sensor network by deploying a few powerful high-end sensors in addition to a large number of low-end sensors. In this paper, we design an efficient routing protocol based on the chessboard clustering scheme, and we compute the minimum node density for satisfying a given lifetime constraint. Simulation experiments show that the chessboard clustering-based routing protocol balances node energy consumption very well and dramatically increases network lifetime, and it performs much better than two other clustering-based schemes. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: heterogeneous sensor networks; cluster; routing protocol; energy consumption

1. Introduction

A wireless sensor network consists of a large number of tiny sensor nodes that perform sensing tasks and transmit the acquired information to a Base Station (BS). Sensor networks have applications in many areas, such as military, homeland security, health care, environment, agriculture, and manufacturing. Sensor nodes are typically powered by batteries and communicate through wireless channels, and are usually scattered densely and statically in the field.

Typical sensors operate on a non-replaceable battery, and in many scenarios the battery can not be recharged. A large proportion of a sensor's energy is consumed in communications [1]. For example, the energy spent by a mote sensor for transmitting 1-bit data over 20 m is equivalent to that of running 1000 CPU instructions [2]. A major design challenge in sensor networks is to increase the operational lifetime of the network. Energy efficient routing can significantly increase sensor network lifetime since data forwarding is an important operation and major source of energy consumption in sensor networks.

Many routing protocols have been proposed for sensor networks, such as directed diffusion [3], LEACH [4], and two-tier data dissemination

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(TTDD) [5]. However, most routing protocols did not consider the uneven energy consumption (UEC) problem in sensor networks. In typical sensor networks, the many-to-one traffic pattern is dominant, that is, a large number of sensor nodes send data to the one (or a few) BS. Sensor nodes near the BS need to relay packets for all other sensors and have much heavier traffic burden. These sensors run out of power much faster than other nodes, and they are referred to as critical nodes. The short lifetime of the critical nodes dramatically reduces the sensor network lifetime.

Furthermore, most existing routing protocols consider homogeneous sensor networks, that is, all sensor nodes have the same capabilities in terms of communication, computation, energy supply, reliability, etc. However, research has shown that homogeneous ad hoc networks suffer from poor fundamental limits and performance, via theoretical analysis [6], simulation experiments, and testbed measurements [7]. Specifically, Gupta and Kumar [6] showed that the per-node throughput in a homogeneous ad hoc network is only $\Theta(1/\sqrt{n\log n})$, where n is the number of nodes.

Recently deployed sensor network systems are increasingly following heterogeneous designs, incorporating a mixture of sensors with widely varying capabilities [8]. For example, a sensor network may include small Mica2 sensors as well as more powerful high-end sensors and robotic nodes [8]. There have been several works on heterogeneous sensor networks (HSN). Rhee *et al.* [9] developed Millennial Net which provides hardware and software architecture that presumes the presence of heterogeneous node energy and communication capabilities. References [10] and [11] present two real sensor networks that utilize heterogeneous nodes for processing and transport tasks. Yarvis *et al.* [12] study design some issues in HSN. However, Reference [12] only discusses a special HSN, that is, HSN where some of the sensor nodes are line powered and have unlimited energy supply, and all other nodes are just one hop away from the line powered nodes.

Clustering-based schemes are promising techniques for sensor networks because of their good scalability and support for data fusion. Data fusion (or in-network processing) combines data from multiple sensors to eliminate redundant information and transmissions, and thus reduces energy consumption in the network. Several clustering-based routing protocols have been proposed for sensor networks, like LEACH [4], TTDD [5], and LRS [13]. LEACH and LRS periodically select cluster- heads from sensors in the network. However, these schemes suffer from overhead of frequent re-clustering. In addition, they do not solve the UEC problem near the BS. The major differences between our Chessboard Clustering (CC) scheme and other clustering-based routing protocols, like LEACH, LRS, and TTDD, are: (1) In CC, physically more powerful H-sensors are the cluster heads, while other protocols need an algorithm to elect cluster heads. (2) In CC, two different sets of clusters are formed at different periods of time to balance node energy consumption.

To achieve better performance, we adopt a heterogeneous sensor network model. In the HSN model, a small number of powerful High-end sensors (H-sensors) are deployed in the field in addition to a large number of Low-end sensors (L-sensors). An H-sensor has much larger transmission range (power), better computation capability, larger storage, more energy supply, and better reliability than an L-sensor. We address the UEC problem by the Chessboard Clustering scheme designed for HSN.

Various energy saving protocols have been proposed for sensor networks. Ye *et al.* [14] proposed PEAS to let redundant sensors go to sleep and save energy. Tian *et al.* [15] proposed node-sleeping scheme based on 'sponsored area'. Our CC scheme can be coupled with their schemes to save more sensor energy.

The rest of the paper is organized as follow. In Section 2, we describe the uneven energy consumption problem and the CC scheme. In Section 3, we present the CC-based routing protocol for HSN. In Section 4, we compute the minimum node density for a given lifetime constraint 4. Performance evaluation is presented in Section 5. Finally, we conclude this paper in Section 6.

2. The Chessboard Clustering Scheme

In this Section, we discuss the uneven energy consumption (UEC) problem in sensor networks and briefly describe the chessboard clustering scheme that solves the UEC problem.

2.1. The UEC Problem

In LEACH [4] and LRS [13], to solve the uneven energy consumption problem (i.e., a cluster head consumes much more energy than a cluster member), periodically different nodes are elected to serve as the cluster head. However, these schemes suffer from the large overhead of frequent re-clustering. Furthermore,

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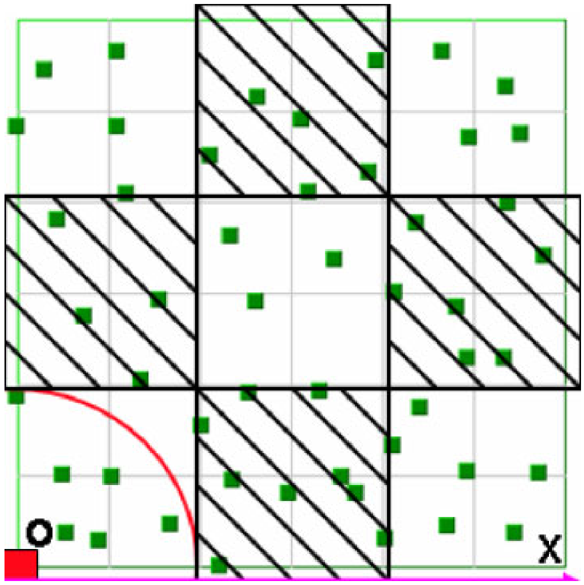

Fig. 1. UEC near the BS.

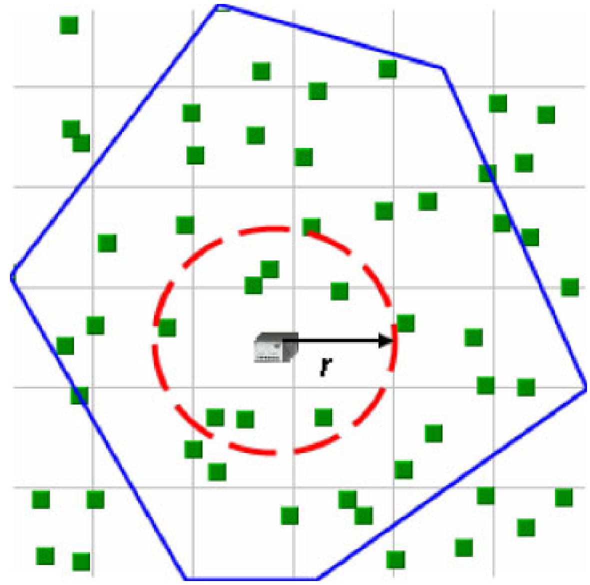

Fig. 2. Critical nodes in a cluster.

rotating cluster-head among sensors does not solve the UEC problem caused by the many-to-one traffic pattern in the network, where the sensors near the BS have much heavier communication burden than other sensors. For example, in Figure 1, the BS is located in the left-bottom corner of the field, and all sensors send data packets to the BS via multi-hops communications. Sensors within the transmission range of the BS are the critical nodes, and they need to relay packets from all other nodes. When all the critical nodes fail, other nodes will be disconnected from the BS, and the whole sensor network becomes unavailable. The UEC problem exists no matter where the BS is located (e.g., at the center).

In an HSN, clusters are formed after sensor deployment. It is natural to let powerful H-sensors serve as cluster heads. When a sufficient number of H-sensors are randomly deployed in the network, there is a high probability that all H-sensors are connected, and the probability goes to one as the number of H-sensors increases [16]. All H-sensors form a communication backbone in the HSN. Each L-sensor sends data to its cluster head, and the cluster head forwards data to the BS via the H-sensor backbone. Since H-sensors have sufficient energy supply, the HSN architecture solves the UEC problem near the BS. Unfortunately, there is another UEC problem in clustering schemes with fixed cluster heads. Consider a cluster in Figure 2, where a node has transmission range r. The nodes that are within the circle (with radius r) from the cluster head are referred to as critical nodes. Every transmission from a node in the cluster to the cluster head has to go through one of these critical nodes. Among all the nodes in a cluster, the critical nodes have the highest burden of relaying data.

Since the critical nodes have much heavier traffic load than other nodes in the cluster, they run out of energy much faster than other nodes. When all critical nodes drain out their energy and become unavailable, other nodes will not be able to send packets to the cluster head, and the entire cluster becomes unavailable even though the remaining energy of many sensor nodes are still high. The remaining energy in the non-critical nodes is wasted.

2.2. The Chessboard Clustering Scheme

To solve the UEC problem within a cluster, we proposed the CC scheme for HSN in Reference [17]. In this subsection, we briefly describe the CC scheme. We consider a heterogeneous sensor network consisting of two types of nodes: a small number of powerful high-end sensors and a large number of low-end sensors. Assume that each sensor is aware of its own location. Sensor nodes can use location services such as References [18,19] to estimate their locations, and a Global Positioning System (GPS) receiver is not required for each node. Location awareness is a basic requirement for many sensor networks, since in many

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cases the sensing data is only meaningful when the location of generating the data is known.

For simplicity, assume that the network is a two-dimension rectangle. As illustrated in Figure 1, denote the left-bottom corner of the network as the original point O, and the horizontal side as the *X*-axis. The sensor network is installed with a chessboard, that is, the sensor network is divided into several small cells, and adjacent cells are filled with different colors—white or black, as illustrated in Figure 1 (where the cross-lines represent black cells). A typical assumption about sensor distribution is the uniform and random distribution. For simplicity, we assume that both L-sensors and H-sensors are uniformly and randomly distributed in the network. Note that our scheme does not depend on such sensor distribution pattern, that is, it also works well for other distributions. Given the point O, the direction *X,* the size of the cell, and the node location, a sensor can determine whether it is in a white cell or a black cell.

The CC scheme includes two phases. The first phase starts after sensor deployment. Only H-sensors in white cells are active, and H-sensors in black cells turn themselves off. All L-sensors are active. Clusters are formed around the H-sensors in white cells, and L-sensors close to these H-sensors become critical nodes. If the network is a two-dimension plane, each L-sensor selects the closest H-sensor (in white cells) as the cluster head (except when there is an obstacle in between), and this leads to the formation of Voronoi cells wherein the cluster heads are the nuclei of the cells.

The second phase starts when H-sensors in white cells run out of energy, H-sensors in black cells wake up and form a different set of clusters in the network. Some previous non-critical L-sensors become critical nodes for the new clusters. Because of the formation of two different sets of clusters during different time periods, previous critical L-sensors become non-critical nodes, and previous non-critical L-sensors become critical nodes. Since critical sensors consume much more energy than other sensors, this switch balances the energy consumption among L-sensors, and dramatically prolongs the network lifetime. The details of the CC scheme can be found in Reference [17].

3. Efficient Routing Based on CC Scheme

In this Section, we present a routing protocol based on the CC scheme in HSN, and it is referred to as CC routing protocol. The CC routing protocol consists of two parts: routing for L-sensors within a cluster; and routing for H-sensors between different clusters. We present them in Subsection 3.1 and 3.2, respectively.

3.1. Routing Within a Cluster

In this subsection, we present a routing scheme for L-sensors to forward data within a cluster, which is referred to as intra-cluster routing. When an L-sensor generates data, it sends the packet to its cluster head (an H-sensor). The packet is forwarded by other L-sensors in the cluster to the H-sensor (say H). We use Figure 3 to illustrate the intra-cluster routing scheme. The basic idea is to let all L-sensors (in a cluster) form a tree rooted at the cluster head H. It was shown in Reference [20] that: (1) If complete data fusion is conducted at intermediate nodes, (i.e., two *k*-bit packets come in, and one *k*-bit packet goes out after data fusion) then a minimum spanning tree (MST) consumes the least total energy in the cluster. (2) If there is no data fusion within the cluster, then a shortest-path tree (SPT) consumes the least total energy. (3) For partial fusion, it is a NP-complete problem of finding the tree that consumes the least total energy.

For sensor networks where the data from nearby sensors are highly correlated (e.g., two *k*-bit packets become one *m*-bit packet, where *m* is close to *k*), a MST can be used to approximate the least energy consumption case. To construct a MST, each L-sensor

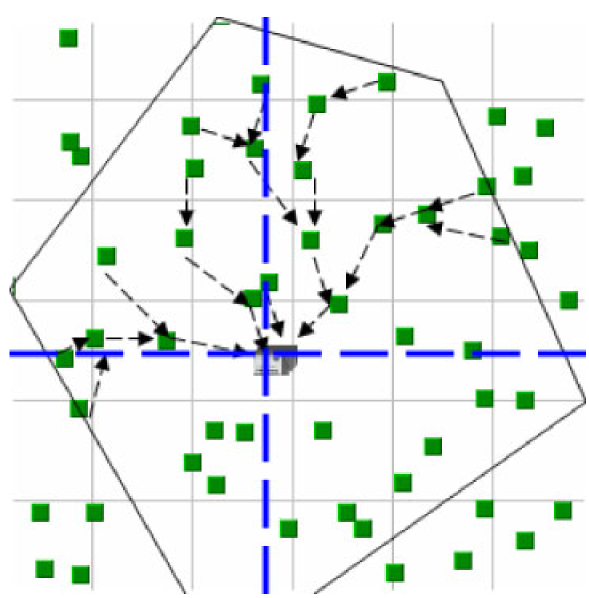

Fig. 3. Intra-cluster routing.

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sends its location information to the cluster head H, and then H runs a centralized MST algorithm to construct a MST. After constructing the MST, H disseminates the tree structure (parent–child relationships) to all L-sensors using one or more broadcasts. The cluster can be divided into several sections, as illustrated by the dotted lines in Figure 3 (where the cluster is divided into four sections). Then H- can notify L-sensors in each section by one broadcast. For sensor networks where the data from nearby sensors have little correlation, a SPT can be constructed by either centralized or distributed algorithms.

Since L-sensors are small, unreliable devices and may fail overtime, robust and self-healing routing protocols are critical to ensure reliable communications among L-sensors. During the tree setup, the MST or SPT algorithm is revised to find more than one parent nodes for each L-sensor. One parent node serves as the primary parent, and other parent nodes serve as backup parents. In case the primary parent node fails, an L-sensor could use a backup parent for data forwarding.

3.2. Routing Between Clusters

The routing scheme for H-sensors to communication with the BS is illustrated in Figure 4, where the small squares represent L-sensors, large rectangular nodes are H-sensors, and the large square at the left-bottom corner is the BS. H-sensors know the location of the BS (e.g., from initial BS broadcast), and communicate

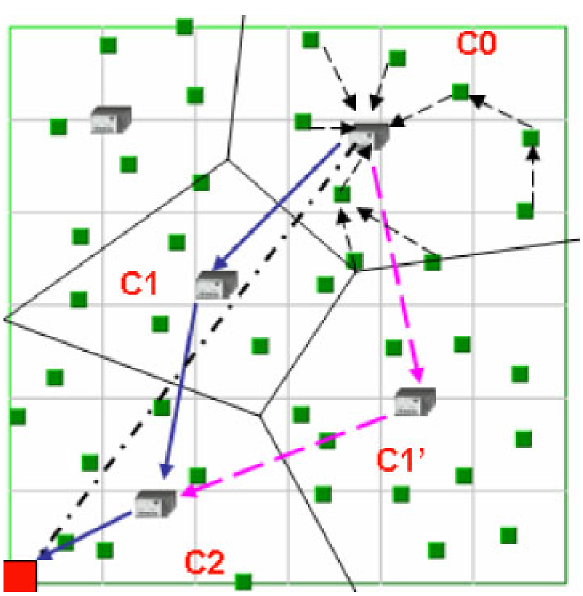

Fig. 4. The routing structure in an HSN.

with the BS via multi-hop transmissions of H-sensors. After initialization, each H-sensor exchanges location information with neighbor H-sensors. When a cluster head wants to send data packets to the BS, it draws a straight line L (the dotted line in Figure 4) between itself and the BS. Line L intersects with several Voronoi cells, and these cells are denoted as $C_0, C_1, \ldots, C_k$, which are referred to as *Relay Cells*. The packet is forwarded from the source cluster head to the BS via the cluster heads in the *Relay Cells*. The H-sensor in C_0 (say H_0) can figure out which cell is the next *Relay Cell* (the cell that intercept with line L), since it knows the locations of neighbor H-sensors. The location of H_0 is included in the data packet. When the H-sensor in C_1 (say H_1) receives the packet, it can figure out which cell is the next *Relay Cell*, based on the locations of H_0, the BS (the first two give the line L), and its neighbors.

To guarantee the delivery, each relay H-sensor is responsible for confirming that its successor has successfully received the packet. This may be implemented by the transmitter's monitoring the packet just sent out to the next node and overhearing if that node has passed it on within a time period. Of course, if a link level acknowledgement is supported by the medium access control (MAC) layer protocol (for instance, IEEE 802.11 MAC), the above passive acknowledgement scheme is unnecessary. The transmitted data packet has to be kept in the buffer before its receipt has been confirmed. The acknowledgement scheme reduces the impact of channel error. If a sender does not get any acknowledgement within a time period, it will re-transmit the data packet once. If the retransmission fails again, the sender will use a backup path.

A backup path is set up as follows (illustrated in Figure 4). The current H-sensor (say H_1) draws a new line L' between itself and the BS, and line L' intersects with several cells $C'_l, \ldots, C'_{k-1}, C_k$. If the next cell is the cell with the failed cluster head, H_1 will use a detoured path to avoid the cell. Otherwise, $C'_l, \ldots, C'_{k-1}, C_k$ are the new *Relay Cells*, and the data packet is forwarded to the BS via the new *Relay Cells*.

An example of routing between clusters is shown in Figure 4, where the cluster head in cell C_0 wants to send data packets to the BS. A straight (dotted) line from the source cluster head to the BS is used to determine the original *Relay Cells*: cells C_0, C_1, C_2. If the cluster head in cell C_1 is not available, the cluster head in cell C_0 will use a backup path C'_1, C_2 (dotted arrows) to connect the BS.

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4. The Minimum Node Density for a Given Lifetime Constraint

An important issue during sensor network design and deployment is to determine the number of sensors (or node density) for a given network lifetime constraint and coverage requirement. In this Section, we will determine the minimum node density of H-sensors and L-sensors, for a given sensor network lifetime constraint. In a typical cluster illustrated in Figure 2, there are two types of sensor nodes: H-sensors and L-sensors. For a given type of H-sensor or L-sensor, the energy supply is assumed to be fixed and known: E_{H} for a H-sensor and E_{L} for a L-sensor. We are interested in determine the node density for H-sensors and L-sensors, such that a given lifetime constraint is satisfied, while the total cost (of sensors) for covering the sensing field is minimized.

4.1. The Network Model

We adopt the following network model to formulate the problem. Assume that the network field is a unit square. The node deployment can be modeled as a two-dimensional homogeneous Poisson point process for each type of nodes, with intensity of λ_{H} and λ_{L} for H-sensors and L-sensors, respectively. There are several ways of defining a Poisson point process, one of which is stated below. First, for any subset A of the network, the distribution of the number of nodes in the set is Poisson with mean $\lambda\|A\|$, where $\|A\|$ is the area of A. Second, given that the number of nodes in such a set A is m, the node locations in A are m mutually independent random variables, each uniformly distributed over A.

Denote the transmission range for an H-sensor and an L-sensor as R and r, respectively. The network operation is divided into rounds. During one round, each L-sensor sends one data packet to its cluster head (an H-sensor) via multi-hop communication, and then the H-sensor aggregates the received data and sends it to the BS via multi-hop of H-sensors. Let C_{H} and C_{L} be the cost per node for H-sensors and L-sensors, respectively. We want to minimize the following cost function:

$$\lambda_{\mathrm{H}} C_{\mathrm{H}} + \lambda_{\mathrm{L}} C_{\mathrm{L}}$$

Based on the results from References [13], to provide connectivity and coverage for the network, the node density should satisfy: $\lambda_{\mathrm{H}} + \lambda_{\mathrm{L}} \geq a$, where a is a constant depending on sensor transmission range, sensor reliability probability (one means the sensor is reliable), and other system parameters.

4.2. Energy Model

L-sensors within range r of a cluster head are referred to as critical nodes, and they have heavier traffic burden and consume energy faster than other L-sensors. Let P_{L} be the average energy spent by a critical node during each round. This consists of energy spent on relaying packets of other nodes that are in the same cluster ($P_{\mathrm{L}}^{\mathrm{r}}$ per packet) and transmitting it's own data ($E_{\mathrm{L}}^{\mathrm{t}}$ per packet, where fixed-size packet is assumed for simplicity). Note that in this paper, we only consider energy consumption for communications, but not for others such as sensing, etc. We assume that L-sensors do not perform data fusion. Let P_{H} denote the amount of energy spent by an H-sensor during a single data gathering round. This consists of energy spent on receiving data from L-sensors in the cluster ($E_{\mathrm{L}}^{\mathrm{r}}$ per packet), in-network processing the received data (E_f per packet), transmitting the compressed data to the BS ($E_{\mathrm{H}}^{\mathrm{t}}$ per packet), and relaying packets for other H-sensors ($P_{\mathrm{H}}^{\mathrm{r}}$). $P_{\mathrm{H}}^{\mathrm{r}}$ depends on the location of the BS and the H-sensor. We assume that the BS is located in one of the corners of the square, as illustrated in Figure 1. Then H-sensors within the distance of R need to relay packets for all other H-sensors, and they are critical H-sensors. The average number of the critical H-sensors is $\lambda_{\mathrm{H}}\pi R^2/4$, and the average number of the non-critical H-sensors is $\lambda_{\mathrm{H}}(1-\pi R^2/4)$ (the network is a unit square). So each critical H-sensor needs to relay packets for $\lambda_{\mathrm{H}}(1-\pi R^2/4)/\lambda_{\mathrm{H}}\pi R^2/4 = 4-\pi R^2/\pi R^2$ non-critical H-sensors on average. Then $P_{\mathrm{H}}^{\mathrm{r}} = (E_{\mathrm{H}}^{\mathrm{r}} + E_{\mathrm{H}}^{\mathrm{t}})(4-\pi R^2)/\pi R^2$, where $E_{\mathrm{H}}^{\mathrm{r}}$ and $E_{\mathrm{H}}^{\mathrm{t}}$ are the energy spent on receiving data from upstream (further away from the BS) H-sensors and transmitting data to downstream H-sensors (or the BS), respectively.

We adopt the radio model used in Reference [4] wherein the energy required to transmit a packet over distance x is $l + \mu x^k$, where l is the constant per packet energy spent in the transmitter electronics circuitry while μx^k is the energy spent in the RF amplifier to counter the propagation loss. The energy required to receive a packet is just l. Then we have, $E_{\mathrm{H}}^{\mathrm{t}} = l + \mu x^k$, $E_{\mathrm{L}}^{\mathrm{t}} = l + \mu r^k$, and $E_{\mathrm{L}}^{\mathrm{r}} = l$.

4.3. The Minimum Node Density

In the CC scheme, L-sensors that locate within a distance of r from cluster heads in white cells serve as critical nodes for about half network lifetime, and then become non-critical nodes for new cluster heads in black cells for another half network lifetime. Most of the previous critical nodes are far away from the new

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cluster heads. For simplicity, we assume that these nodes are boundary nodes (locate at the boundary of clusters) in the second half of the network lifetime, which only send their own packets but do not relay packets for other L-sensors. Assume that the lifetime constraint of a sensor network is that the network must operate for at least T rounds. During the first half of the network lifetime, the energy spent by a critical node C is $P_L \cdot T/2$. During the second half of the network lifetime, the energy spent by node C as a boundary node is $E_L^t \cdot T/2$. Note that if C is not a boundary node in the second half, more energy will be consumed. Thus, the total energy consumption for such a node is $P_L \cdot T/2 + E_L^t \cdot T/2$. To ensure a lifetime of at least T rounds, we have for critical L-sensors,

$$E_L \geq P_L \cdot \frac{T}{2} + E_L^t \cdot \frac{T}{2} \tag{1}$$

For an H-sensor in CC scheme, it only serves as a cluster head for half of the network lifetime, we have:

$$\frac{E_H}{P_H} \geq \frac{T}{2} \tag{2}$$

We also assume that the cluster heads coordinate MAC and routing in their clusters so that no energy is wasted on packet collisions or idle listening (ideal MAC assumption). A cluster head performs fusion of the data packets that it receives from all the sensors in its cluster, and transmits a single packet to the BS during each round. We have,

$$P_L = E_L^t + P_L^r \tag{3}$$

$$P_H = \mathrm{E}[N_L](E_L^r + E_f) + E_H^t + P_H^r \tag{4}$$

where $\mathrm{E}[N_L]$ is the expected number of L-sensors in a typical cluster. Based on the results from References [21] and [22], we have $\mathrm{E}[N_L] = \lambda_L/\lambda_H$, and the expected number of L-sensors located within a distance of r from an H-sensor (critical nodes) is

$$\mathrm{E}[N_L(r)] = \frac{\lambda_L}{\lambda_H(1 - \mathrm{e}^{-\lambda_H \pi r^2})}$$

Thus the average relaying load on each critical node is

$$P_L^r = (E_L^r + E_L^t)\left(\frac{\mathrm{E}[N_L] - \mathrm{E}[N_L(r)]}{\mathrm{E}[N_L(r)]}\right) = \left(E_L^r + E_L^t\right)\left(\frac{\mathrm{e}^{-\lambda_H \pi r^2}}{1 - \mathrm{e}^{-\lambda_H \pi r^2}}\right)$$

Plug the results into Equations (3) and (4), we have,

$$P_L = E_L^t + P_L^r = E_L^t + (E_L^r + E_L^t)\left(\frac{\mathrm{e}^{-\lambda_H \pi r^2}}{1 - \mathrm{e}^{-\lambda_H \pi r^2}}\right)$$

$$P_H = \frac{(E_L^r + E_f)\lambda_L}{\lambda_H} + \frac{E_H^t + (E_H^r + E_H^t)(4 - \pi R^2)}{\pi R^2}$$

From Equation (1), we have

$$E_L \geq P_L \cdot \frac{T}{2} + E_L^t \cdot \frac{T}{2}$$

$$\Leftrightarrow \frac{2E_L}{T} \geq P_L + E_L^t = 2E_L^t + (E_L^r + E_L^t)\left(\frac{\mathrm{e}^{-\lambda_H \pi r^2}}{1 - \mathrm{e}^{-\lambda_H \pi r^2}}\right)$$
$$\Leftrightarrow \frac{2E_L/T - 2E_L^t}{E_L^r + E_L^t} \equiv C_0 \geq \frac{\mathrm{e}^{-\lambda_H \pi r^2}}{1 - \mathrm{e}^{-\lambda_H \pi r^2}}$$
$$\Leftrightarrow \lambda_H \geq \ln \frac{1 + C_0/C_0}{(\pi r^2)}$$

Thus, the minimum density of H-sensors should be:

$$\lambda_H^* = \ln \frac{1 + C_0/C_0}{(\pi r^2)} \tag{5}$$

Note that the actual density of H-sensors for deployment should be $2\lambda_H^*$, since λ_H^* of H-sensors are used only for half network lifetime in CC scheme. After determining the density of H-sensors, the density of L-sensors can be determined as following.

From Equation (2) we have,

$$\frac{E_H}{P_H} \geq \frac{T}{2} \Leftrightarrow \frac{2E}{T} \geq P_H \Leftrightarrow \frac{2E}{T} \geq \frac{(E_L^r + E_f)\lambda_L}{\lambda_H} + E_H^t + \frac{(E_H^r + E_H^t)(4 - \pi R^2)}{\pi R^2}$$
$$\Leftrightarrow \frac{2E_H/T - E_H^t - (E_H^r + E_H^t)(4 - \pi R^2)/\pi R^2}{E_L^r + E_f}\lambda_H \geq \lambda_L$$
$$\Leftrightarrow \beta\lambda_H \geq \lambda_L$$
$$\left(\beta \equiv \frac{2E_H/T - E_H^t - (E_H^r + E_H^t)(4 - \pi R^2)/\pi R^2}{E_L^r + E_f}\right)$$

that is, the L-sensors density should be no greater than $\beta\lambda_H$.

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Considering the coverage condition $\lambda_H + \lambda_L \geq a$, we have,

- if $\beta\lambda_H^* \geq a - \lambda_H^*$, where λ_H^* is obtained from Equation (5), then λ_L should satisfy: $\beta\lambda_H^* \geq \lambda_L \geq a - \lambda_H^*$, and the minimum density of L-sensors is $a - \lambda_H^*$.
- if $\beta\lambda_H^* < a - \lambda_H^*$, then the density of H-sensor λ_H should be increased such that $\beta\lambda_H = a - \lambda_H$, that is $\lambda_H = a/(1+\beta)$, and the density of L-sensors is $\beta\lambda_H = a\beta/(1+\beta)$.

4.4. Related Work

In Mhatre *et al.* [21] studied the node densities and energies in heterogeneous sensor networks to guarantee a lifetime. There are several differences between our work and Reference [21], and we list the differences in the following.

- The authors in Reference [21] assume that each cluster head can directly communicate with the BS. However, this assumption is either invalid for many large-scale sensor networks that cover a large area, or too costly because of the very long transmission range of the cluster heads. We do not make such an assumption. Instead, in our model the cluster heads use multi-hop to communicate with sinks. Since cluster heads also use multi-hop communication, the energy spent by cluster heads also includes the part for relaying packets for other cluster heads.
- In Reference [21], the authors considered the sensor energy supplies as variables, and try to determine the optimum value for the energy supplies. However, the energy supply should be fixed for a specific type of sensor node, or with very limited options. For example, the MICA2-DOT sensors use one 3V coin cell battery, and the MICAz sensors use 2 AA batteries [23]. Allowing the sensor energy supply to be any value is not reasonable. Thus, we think it is more reasonable to consider the sensor energy supply as a given value.
- Reference [21] adopts the usual clustering scheme to form clusters, and a cluster becomes unavailable when the critical nodes fail. In our approach, CC scheme is used to form two different sets of clusters, critical nodes in the first phase become boundary nodes in the second phase. The node energy consumption is well balanced among all L-sensors in a cluster.

5. Performance Evaluation

We evaluate the performance of the CC routing protocol through simulation experiments, and compare CC with two other clustering-based routing schemes—LEACH and LRS. LRS is a chain-based three-level hierarchical protocol proposed by Lindsey *et al.* [13]. In this protocol, sensor nodes are initially grouped into clusters based on their distances from the BS. A chain is formed among the sensor nodes in a cluster at the lowest level of the hierarchy. Gathered data, moving from one node to another, get aggregated, and finally reach a designated leader in the chain, that is, the cluster head. At the next level of the hierarchy, the leaders from the previous level are clustered into one or more chains, and the data are collected and aggregated in each chain in a similar manner.

The CC routing protocol was implemented in QualNet [24]. For comparison, LEACH and LRS were also implemented in QualNet, and the underlying MAC is the modified 802.11 Distributed Coordination Function (DCF) (RTS with the next_cell field). For CC, the default simulation testbed has 1 BS, 1000 L-sensors, and 40 H-sensors randomly and uniformly distributed in a $300\,m \times 300\,m$ area. Since LEACH and LRS are designed for homogeneous sensor networks, for fair comparison, 1500 L-sensors are distributed in the $300\,m \times 300\,m$ area. Here, we consider the higher cost of H-sensors compared to L-sensors, and 500 additional L-sensors are used in LEACH and LRS to make the investment similar. Of course the actual costs of H-sensor and L-sensor, which is out of the scope of this paper, depend on the types of sensors, manufacture, etc.

Each simulation runs for 2000 s, and each result is averaged over 10 random network topologies. Each L-sensor in CC generates three data packets per second, and each L-sensor in LEACH or LRS generates two data packets per second. Thus, the total volume of data generated in CC is the same as that in LEACH and LRS. All the data packets have the same length—32 bytes. For intra-cluster routing of the CC scheme, a centralized shortest-path tree (SPT) algorithm is used to simulate cases without data fusion. The transmission range of an H-sensor and an L-sensor is 80 and 20 m, respectively. Both H-sensors and L-sensors have a fixed amount of energy supply—50 J and 2 J, respectively. High-end sensors are assumed to have sufficient energy supply, for example, sensors with a solar cell to recharge the battery as needed.

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Our energy model for the L-sensors is based on the first order radio model described in Reference [4]. A sensor consumes $\in_{elec} = 50$ nJ/bit to run the transmitter or receiver circuitry and $\in_{amp} = 100$ pJ/bit/m^2 for the transmitter amplifier. Thus, the energy consumed by a L-sensor in receiving a k-bit data packet is given by, $Rx = \in_{elec} \cdot k$, while the energy consumed by sensor i in transmitting a data packet to sensor j is given by, $Tx = \in_{elec} \cdot k + \in_{amp} \cdot d_{i,j}^2 \cdot k$, where $d_{i,j}$ is the distance between nodes i and j. The energy parameters for H-sensors are $\in_{elec} = 100$ nJ/bit and $\in_{amp} = 200$ pJ/bit/m^2.

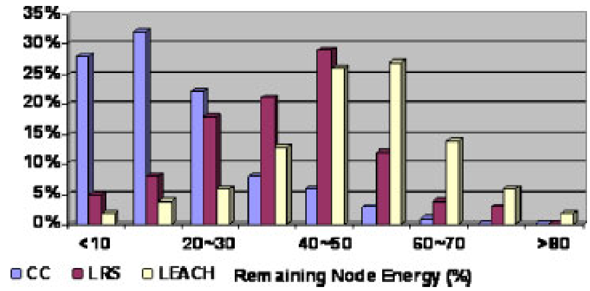

Fig. 6. The distribution of remaining node energy.

5.1. Network Lifetime

First we compare the network lifetime for different sensor node density. The network lifetime here is defined as the time that no sensor can send packets to the BS. For the fixed 300 m × 300 m routing area, the number of L-sensors in CC varies from 500 to 2000 with an increment of 500, while the number of H-sensors remains 40 for all cases. The numbers of L-sensors in LEACH and LRS are always 1.5 times that in CC, that is, varies from 750 to 3000 with an increment of 750. The network lifetimes under the three routing protocols are plotted in Figure 5, where the x-axis is the number of L-sensors in CC.

As we can see, the network lifetimes under all the routing protocols increase as sensor density increases. With a higher node density, more sensors are available to forward packet to the BS, and hence the network lifetime increases. Figure 5 also shows that CC has much longer lifetime than LRS and LEACH. In LRS and LEACH, L-sensors serve as cluster heads in turn to balance node energy consumption and to ensure the availability of cluster heads. However, since L-sensor has limited energy supply, the cluster heads need to be re-elected periodically. Even though each L-sensor only serves as cluster head once, there are 2000 elections in a 2000-node network. Each cluster head election introduces large overhead in the network and drains lots of energy from nearby sensor nodes. A large number of elections cause sensor nodes consume too much energy and die out quickly. While in CC, only the powerful H-sensors serve as cluster heads, so there is only one election for each H-sensor. That is, in the simulation there are only 40 cluster head elections in CC. The overhead of clustering in CC is very small. Thus, the network lifetimes in LRS and LEACH are much shorter than that in CC. Furthermore, the CC scheme balances energy consumption among L-sensors very well, and prevents some nodes from running out of energy too soon. To sum up, because of the small overhead from clustering and the well balance of L-sensor energy consumptions, the CC scheme can significantly increase sensor network lifetime.

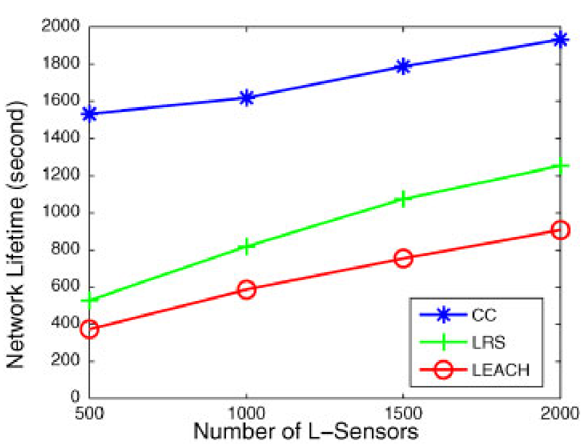

Fig. 5. Network lifetime for different node densities.

5.2. Remaining Node Energy

Figure 6 reports the distribution of the remaining node energy when the sensor network became unavailable. The x-axis is the remaining sensor energy in terms of the percentage of the initial L-sensor energy, and y-axis is the percentage of L-sensors. We can see that most sensors in CC have remaining energy below 20%, while in LRS most nodes have remaining energy between 20% and 50%, and in LEACH most nodes have 30% to 70% energy left. Figure 6 shows that CC balances the energy consumption among nodes better than both LRS and LEACH, and LRS performs better than LEACH. In typical sensor networks, sensors send packets to the BS via multi-hop communications. The failure of any node in the path will cause the route unavailable. If the node energy drain is not well

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balanced, then some nodes will die too soon and cause route unavailable or even the network disconnected. Besides minimizing the total energy consumption in the network, balancing node energy consumption is also very important for increasing sensor network lifetime.

5.3. Packet Delivery Ratio

To evaluate the effectiveness of CC routing protocol, we measure the packet delivery ratio of CC under different node density, and compare the performance with LEACH and LRS. The packet delivery ratio is defined as the ratio between the number of packets generated in the network and the number of packets received by the BS. In the simulation, the change of node density is the same as that in Subsection 5.1. that is, the number of L-sensors in CC varies from 500 to 2000 with an increment of 500. The number of H-sensors remains 40 for all cases. And the number of L-sensors in LEACH and LRS varies from 750 to 3000 with an increment of 750. The packet delivery ratio is calculated with the data from 0 to 300 s, during which the sensor network is always connected for all routing schemes. The results are plotted in Figure 7, where the *x*-axis is the number of L-sensors in CC.

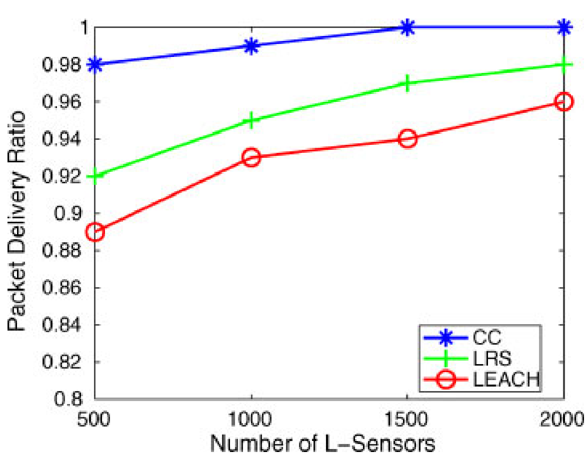

Fig. 7. Packet delivery ratio.

Figure 7 shows that CC always achieves very high packet delivery ratio, close to one for all tested node densities. In CC, L-Sensors send packets to the cluster heads—H-sensors, and H-sensors forward packets to the BS. H-sensors have longer transmission range and higher data rate than L-sensors, thus there is few congestion happens in CC. In LEACH and LRS, cluster head elections occur frequently and cause large overhead. Some sensors die out too early and cause packet lost. When the density of L-sensors increases, the effect of node failures on packet delivery ratio is reduced. This is the reason that the packet delivery ratio in LEACH and LRS increases as node density increases. In LEACH and LRS, a large number of sensors need to communicate with the BS and this may cause interference and congestion in the network, and thus causes more packets lost. This is another reason that LEACH and LRS have lower packet delivery ratio than CC.

5.4. The Minimum Node Density for a Given Lifetime Constraint

We also run simulations to evaluate the node density results for a given lifetime constraint (as discussed in Section 4). Recall that we assumed a unit square in Section 4. In our simulation, the testbed has an area of $A = 300\,\text{m} \times 300\,\text{m}$. If the total area A is normalized to one, then all the distances should be divided by a normalizing factor $\sqrt{A} = 300$. Thus, the transmission range of an H-sensor and an L-sensor is $80/300 = 0.267$ and $20/300 = 0.067$, respectively. By using the node density results from Section 4 and the energy model at the beginning of Section 5, we calculate the minimum number of H-sensors and L-sensors for different lifetime requirements. Then simulations are run by deploying the calculated number of H-sensors and L-sensors, and the actual network lifetime is recorded. To satisfy a coverage condition, we need $\lambda_H + \lambda_L \geq a$, where a depends on the required coverage degree, node sensing range, and other parameters. For simplicity, in the computation we assume the coverage requirement is always satisfied. The experimental results are presented in Table I.

Table I. Minimum number of nodes for given lifetime requirements

Required Lifetime (round)	10 000	20 000	30 000	40 000	50 000
Actual lifetime (round)	9628	19015	27491	36842	46326
Number of H-sensors	5	10	15	22	28
Number of L-sensors	198	410	638	886	1158

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In Table I, the 1st row is the lifetime requirement, in terms of round. The 2nd row is the actual network lifetime recorded in the simulation, and the lifetime is defined as the time when the first critical L-sensor or H-sensor dies. The last two rows are the numbers of H-sensors and L-sensors which are calculated based on the lifetime requirement. Table I shows that the actual lifetime is very close to the required lifetime, which validates the results of minimum node density in Section 4. In addition, we can see that the actual lifetime is always a little bit shorter than the required lifetime. Since H-sensors and L-sensors are randomly and uniformly distributed in the network, some clusters may have more L-sensors than other clusters, and some critical L-sensors may need to relay more traffic than other critical L-sensors. A critical L-sensor will die sooner if it has more relay traffic than average. This is why the actual lifetime is slightly smaller than the expected value. The simulation result suggests that we should deploy a few extra sensors (in addition to the calculated node density) to provide a given lifetime requirement.

6. Conclusions

In this paper, we present an energy-efficient, self-healing CC routing protocol for heterogeneous sensor networks, which can increase network lifetime by balancing sensor energy consumption. In CC, two different sets of cluster heads are formed during different time periods to balance the energy consumption of L-sensors. The CC routing protocol includes intra-cluster and inter-cluster routing schemes. We compute the minimum node density for H-sensors and L-sensors to satisfy a given lifetime constraint. Our simulation experiments show that CC balances node energy consumption very well and substantially increases network lifetime, and it performs much better than two other clustering-based schemes—LEACH and LRS. The simulation also validates our computation results of the minimum node density for a given lifetime constraint.

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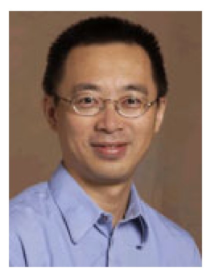

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