Journal of Southeast University (English Edition) Vol. 25, No. 4, pp. 445 – 450 Dec. 2009 ISSN 1003—7985

Grid-based energy-aware routing in wireless sensor networks

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Abstract: The model of energy cost in a wireless sensor network (WSN) environment is built, and the energy awareness and the wireless interference mainly due to different path loss models are studied. A special case of a clustering scheme, a two-dimensional grid clustering mechanism, is adopted. Cluster-heads are rotated evenly among all sensor nodes in an efficient and decentralized manner, based on the residual energy in the battery and the random backoff time. In addition to transmitting and receiving packets within the sensors' electrical and amplification circuits, extra energy is needed in the retransmission of packets due to packet collisions caused by severe interference. By analysis and mathematical derivation, which are based on planar geometry, it is shown that the total energy consumed in the network is directly related to the grid-structure in the proposed grid based clustering mechanism. The transmission range is determined by cluster size, and the path loss exponent is determined by nodal separation. The summation of overall interference is caused by all the sensors that are transmitting concurrently. By analysis and simulation, an optimal grid structure with the corresponding grid size is presented, which balances between maximizing energy conservation and minimizing overall interference in wireless sensor networks.

Key words: wireless sensor networks; grid; energy consumption; interference; packet loss

Wireless sensor networks (WSNs) are mainly characterized by their limited and non-replenishable energy supply. Clustering and partitioning are common techniques used in wireless networks that can extend the lifespan of the whole network, especially in large-scale multihop environments.

Several protocols have been proposed in the literature, with the objective of maximizing the sensor network lifetime by adopting cluster-based network architectures. One of the well known clustering protocols is LEACH[1]. A further improvement of this protocol known as LEACH-C is proposed in Ref. [2]. The limitation of both LEACH and LEACH-C is that cluster-heads communicate with sink directly, which is not practical in large networks.

TTDD proposed by Luo et al. [3] provides scalable and efficient data delivery to multiple mobile sinks. However, TTDD's source based grid needs to be changed when the target moves, and its target is to handle sink mobility instead of energy conservation, which is a critical problem in wireless sensor networks.

Zhou et al.'s work EEDD[4] provides a comprehensive study of target tracking from grid formation, leader election, sleep scheduling, data dissemination and routing to target and inquirer mobility. However, the proposed scheme is quite independent of the transmission range of the wireless sensors, which affects the sleep scheduling and grid structure.

In this paper, a grid-based clustering mechanism is adopted, in which clusters are equally-sized square grids in a two-dimensional planar. The intuition behind this mechanism is that, when presenting a wireless sensor network, we want to depict an area totally covered by radio without any gaps. We first divide the network topology into equally-sized cluster grids, each with the size of $s \times s$. For communication of neighboring clusters, we set the cluster size $s \leqslant r/\sqrt{8}$; therefore nodes in different clusters can talk to one another in horizontal, vertical and diagonal directions (see Fig. 1).

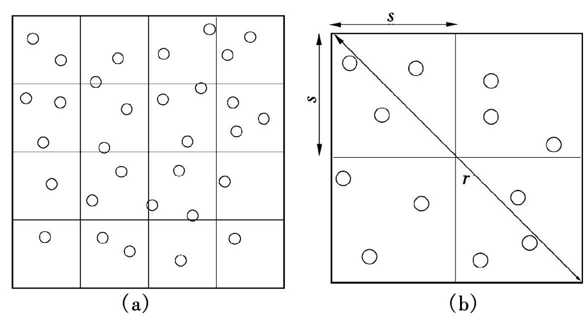

Fig. 1 Grid-based clustering. (a) Grid-cluster topology; (b) A cluster with the size of $s \leqslant r/\sqrt{8}$

Our focus is, how large r should be, or, how the transmission range matters when it comes to the issue of energy efficiency. There is a tradeoff between energy consumption and the number of hops, and there is an optimal transmission range based on grid size in a planar network clustering mechanism.

1 System Design

1.1 Overview

We build our system on the grid-based clustering mechanism, with dynamic cluster-head election within each cluster, and multihop routing between clusters. There are totally three modules for different functional purposes (see Fig. 2).

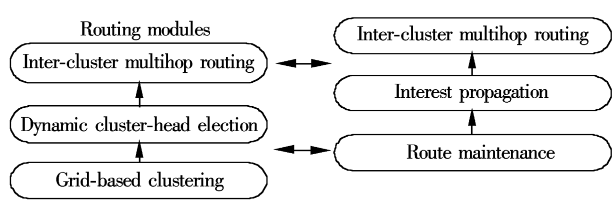

Fig. 2 Relationship between routing modules and phases

Received 2009-06-03.

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Citation: Liu Shu, Zhuang Yanyan, Wang Fangfang, et al. Grid-based energy-aware routing in wireless sensor networks[J]. Journal of Southeast University (English Edition), 2009, 25(4): 445 – 450.

1.2 Cluster-head election

The election algorithm adapts to the node energy level in the network and rotates the role of a cluster-head accordingly, with the aim of even energy distribution. When a node boots up, it starts its life cycle either as being a regular working node, or as a cluster-head working with a pre-configured duty cycle. Whenever a cluster-head finishes its duty, it retires and the rest of the nodes in the cluster compete for the cluster-head position. This competition is energy-aware: all the nodes fire a back-off timer according to their current energy remaining in the battery.

$$t = T_{start} + k(T_{end} - T_{start}) \tag{1}$$

Here k is a random value between [0, 1], so t is any value that locates between T_{start} and T_{end}. Tab. 1 shows how the starting and ending time is set with less residual energy. A node has to wait a longer time till its back-off timer expires. Once any node's timer counts down to 0, the node which first broadcasts a declaration message becomes the cluster-head in the next round. This process depends on local battery information, instead of exchanging control message network wide.

Tab. 1 Back-off time and residual energy

Battery voltage/V	T_{start}/μs	T_{end}/μs
$v > 3.15$	6	15
$3.00 < v \leqslant 3.15$	16	25
$2.70 < v \leqslant 3.00$	26	35
$2.50 < v \leqslant 2.70$	36	45
$2.20 < v \leqslant 2.50$	46	55
$v \leqslant 2.20$	56	65

Through our experiments, we found that, when power voltage becomes lower than 2.2 V, the node almost dies. Then we obtain $T_{start} = 5.6$ ms and $T_{end} = 6.6$ ms, the longest back-off time. Thus, the node would not become a cluster-head in the next duty cycle.

1.3 Multihop routing

In wireless sensor networks, any node will be the potential data source. Our assumption of network-wide sink location awarenesss, as well as the good property of grid structure, allows packets to be forwarded in a pre-defined manner.

Initially, each node sets its cost to ∞, with γ as the deferral time coefficient. Once a node hears an interest propagation message, it defers its forwarding for a time proportional with the optimal cost to reach the next hop. By setting γ properly (according to our experiment $\gamma = 10$), each node broadcasts only once. Fig. 3 shows the process of route set-up.

1) Initially, the cost at X is L_X. The costs at Y and Z are ∞. At time t, X broadcasts and the message is heard by Y and Z. Y sets its cost L_Y as $L_X + 2.5$ where 2.5 is the link cost between X and Y, and sets its timer to expire after $\gamma \times 2.5 = 25$ μs. Similarly, Z sets its cost as $L_X + 5$ and its timer as 50 μs.

2) At $t + 25$, Y's timer expires. Y sets X as its last hop and broadcasts. When Z hears it, it finds $L_Z = L_X + 5 > L_Y + 1$, so it updates cost as $L_Y + 1$, and sets its timer to expire after $\gamma \times 1 = 10$ μs.

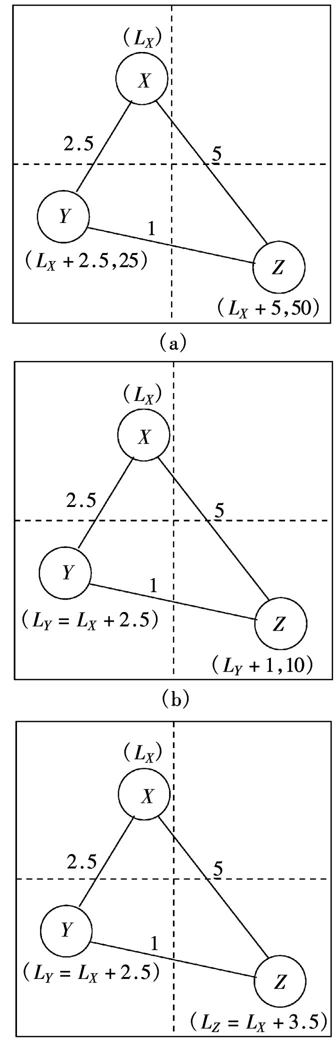

Fig. 3 Route set-up. (a) At t; (b) At $t+25$; (c) At $t+35$

3) At $t + 35$, Z's timer expires. Z sets Y as its last hop and broadcasts with its minimum cost.

2 Performance Analysis

In this section, we model the energy needed for packet transmission, reception, etc., as well as the extra portion for re-transmission due to interference. By analyzing the trade-off between multihop and wireless interference, we find an optimal transmission range, as well as the grid size for the grid-based clustering mechanism.

2.1 Model background

All nodes are homogeneous, and they have the same transmission range r and power P_t for communication, with the same initial energy E_0. An omnidirectional antenna is used. The sink node is stationary and all other nodes are aware of its location. With ideal physical channels and MAC layers, transmission errors are caused by interference. In a wireless channel, the electromagnetic wave propagation can be modeled as falling off a power law function of the distance between the transmitter and the receiver. No matter which model is used (direct line-of-sight or multi-path fading) [1], the received power decreases as the distance between the transmitter and the receiver increases.

According to the radio energy adopted by Ref. [1], the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics. Thus, to transmit an l-bit message over a distance d, the radio expends

$$E_{tx} = E_{tx\_e}(l) + E_{tx\_amp}(l, d) = lE_e + E_{tx\_amp}(l, d) \quad (2)$$

2. 2 Energy for transmission and reception

In electrical operation of wireless sensor nodes, energy consumption is mainly spent in three categories: energy for transmitting/receiving packets, and energy used in the electrical circuit. We can analytically determine energy consumption in sensor networks using the computation and communication energy models developed in the previous section.

1) Energy consumption of cluster-head. Assume that nodes are distributed uniformly in an $L \times L$ region, with a constant node distribution ρ. There are ρs^2 nodes in each cluster. Each cluster-head dissipates energy receiving signals from the nodes and transmitting the received data to a neighboring cluster-head. For data transmission, whether the following Friis free space or two-ray ground model depends on the separation between two communicating cluster-heads. Therefore, the energy dissipated in the cluster-head node during a single time slot is

$$E_{ch} = lE_e\rho s^2 + [lE_e + E_{tx\_amp}(l, d_{int})]\rho s^2 = [2lE_e + E_{tx\_amp}(l, d_{int})]\rho s^2 \quad (3)$$

where l is the number of bits in each data message, and d_{int} is the distance between the neighboring cluster-heads.

2) Energy consumption of working node. Each working node only needs to transmit its data to the cluster-head. And the energy dissipation can be expressed as

$$E_{wk} = lE_e + E_{tx\_amp}(l, d_{inn}) \quad (4)$$

where d_{inn} is the average distance from the node to the cluster-head. In general, the sensing area is an $L \times L$ region and the area occupied by each cluster is approximately s^2. Therefore, the expected distance raised to the power of α is given by

$$E[d^\alpha] = \frac{\iint[(x_1 - x_2)^2 + (y_1 - y_2)^2]^{\alpha/2}\mathrm{d}D_1\mathrm{d}D_2}{|D_1||D_2|} \quad (5)$$

where $|D_1|$ and $|D_2|$ are the size of the area where (x_1, y_1) and (x_2, y_2) resides, respectively; α can be either 2 or 4, depending on the channel propagation model.

3) Average number of hops. There are approximately L^2/S^2 clusters in the network, and each packet has to traverse $E[H]$ hops to reach its destination. Without opportunistic routing, packets can only jump between one grid at a time. Then the probability of having a route of length i hops from the sender to the destination is proportional to the number of relay nodes in the area inscribed by two concentric "grid circles" of radii is and $(i-1)s$:

$$p(H = i) = \frac{\rho[(is)^2 - ((i-1)s)^2]}{\rho L^2} = \frac{s^2(2i-1)}{L^2} \quad (6)$$

As a result, the expected hop count is

$$E[H] = \sum_{i=1}^{L/s} p(H = i)i = \frac{s^2}{L^2}\sum_{i=1}^{L/s}(2i-1)i \approx \frac{2L}{3s} \quad (7)$$

As a comparison, packets jump at most two consecutive grids at a time in opportunistic routing. The average hop count is thus in the order of $2L/(3r)$, reducing the number of hops significantly.

4) Integration. For all the transmission and reception tasks, the total energy consumed by all the nodes in the network during each time slot is

$$E_{tx\_rx} = \frac{L^2}{s^2}E_{ch}E[H] + \left(\rho L^2 - \frac{L^2}{s^2}\right)E_{wk} \quad (8)$$

Total energy consumption is $L^2\left[\rho\frac{2L}{3s}(2lE_e + E_{tx\_amp}(l, d_{int})) + \left(\rho - \frac{1}{s^2}\right)(lE_e + E_{tx\_amp}(l, d_{inn}))\right]$.

Fig. 4(a) shows the relationship between E_{tx_rx} and grid size s. There are three cases in which the total energy consumption is affected by node separation.

In Fig. 4(b), we show two examples, $s = r/\sqrt{8}$ and $s = r/\sqrt{15}$. If grids are smaller, the overall energy consumption is lower, but a larger transmission range is needed to reach the optimal value.

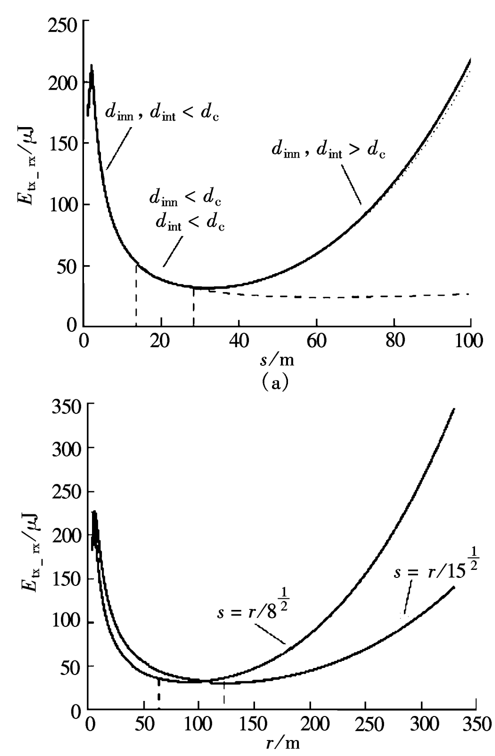

Fig. 4 Energy consumption for transmission and reception. (a) Relationship between E_{tx_rx} and grid size s; (b) Relationship between E_{tx_rx} and Tx range r

2.3 Analysis of interference and collision

Under isotropic path loss, the channel gain from node x to node y is

$$G(x,\ y) = \left[\frac{d(x,\ y)}{d_0}\right]^{-\alpha} \tag{9}$$

where $d(x,\ y)$ is the distance between x and y, and d_0 is a constant; α is the path loss exponent ($\alpha = 2$ for free-space model and $\alpha = 4$ for two-ray ground model). From this equation we see that the channel gain is inversely proportional to the distance between the transmitter and the receiver. We first model the interference at a given node, and then calculate the packet loss probability which leads to retransmission and extra energy consumption.

2.3.1 Modeling of interference

Assume that I_i is the total interference at node i in a given time slot. I_i is the sum of constant thermal noise N_i and interference due to data transmissions by other nodes during this time slot. Thus,

$$I_i = \overline{P_r} = \sum_{j \in \{N-i\}} P_t G(j,\ i) = \sum_{j \in \{N-i\}} \frac{P_t d_0^{\alpha}}{d(i,\ j)^{\alpha}} \tag{10}$$

1) Inner-cluster interference. This portion of interference is the current transmission signal received, when one node is scheduled to communicate with the cluster-head inside this cluster. Therefore,

$$E\left[\sum G(j,\ i)_{\text{inn}}\right] = \frac{P_t d_0^{\alpha}}{E[d_{\text{inn}}^{\alpha}]} \tag{11}$$

2) Inter-cluster interference. Totally, in all the remaining $L^2/s^2 - 1$ clusters, there is at most one on-going transmission that contributes to inter-cluster interference. Thus

$$E\left[\sum G(j,\ i)_{\text{int}}\right] = \frac{P_t d_0^{\alpha}}{E[d_{\text{int}}^{\alpha}]}\left(\frac{L^2}{s^2} - 1\right) \tag{12}$$

Therefore the average interference at node i during a time slot is

$$I_i = P_t d_0^{\alpha}\left[\frac{1}{E[d_{\text{inn}}^{\alpha}]} + \frac{1}{E[d_{\text{int}}^{\alpha}]}\left(\frac{L^2}{s^2} - 1\right)\right] \tag{13}$$

Fig. 5 shows the interference level derived from Eq. (13).

2.3.2 Modeling of packet loss probability

A wireless signal transmission is successful, provided that throughout the duration of the packet transmission $P_{ri}/(N + I_i) \geqslant \beta$. Here β is the SINR threshold at the receiver side; P_{ri} is the received signal strength; N is the thermal noise and $E[I_i]$ is the sum of all on-going interference at node i.

Assuming that many small, independent transmitting signals additively contribute to the interference at each independent receiver, the use of the normal model can be theoretically justified by the central limit theorem (CLT)[5]. Tab. 2 shows some sample values of grid size, transmission range, mean and variance of accumulated interference. Variance ranges between 0.11 and 0.36. In Fig. 6, there are the corresponding probability density functions (PDF) of these sample values.

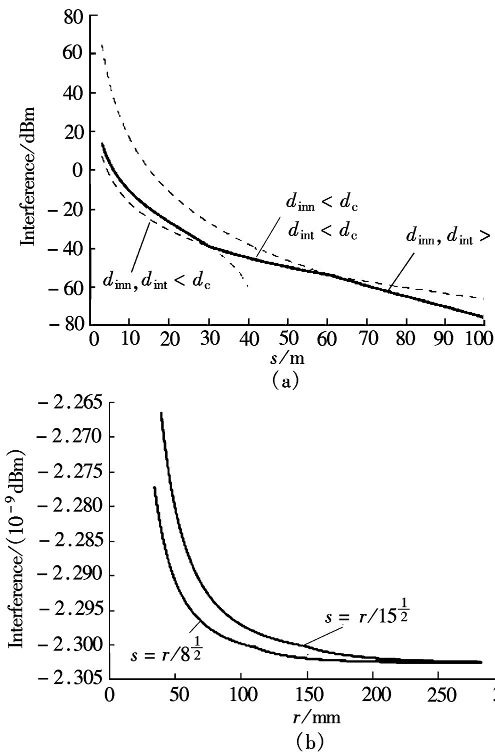

Fig. 5 Interference for transmission and reception. (a) Relationship between interference and grid size s; (b) Relationship between interference and Tx range r

Tab. 2 Sample mean and variance

Grid size/m	Tx range/m	Mean	Variance
8	22.6	−6.64	0.122
12	33.9	−7.44	0.159
16	45.3	−8.16	0.206
20	56.6	−8.75	0.281
24	67.9	−9.24	0.362
30	84.9	−9.90	0.271

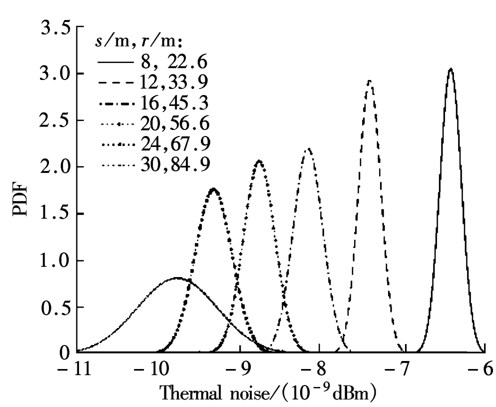

Fig. 6 PDF of different grid sizes (Tx range)

For the estimation of I_i at each node, we therefore model it as a normal random variable as follows. The sum of L^2/s^2 random interference values is given by $I_i = \sum_{j=1,\ j\neq i}^{L^2/s^2} P_r(j,\ i)$, each having finite values of expectation μ and σ^2. With Ref. [5] we know that $I_i \propto N(\mu,\ \sigma^2)$. Therefore, the probability of a successful transmission is

$$p = P_r(I_i \leqslant P_{ri}/\beta - N) = \varphi\left[\frac{P_{ri}/\beta - N - \mu}{\sigma}\right] \qquad (14)$$

where $\varphi(x)$ is the standard normal CDF.

1) SINR threshold. According to Shannon's theorem[6], the value of the SINR threshold is determined as

$$C = B\log_2(1 + \text{SINR}) \qquad (15)$$

where C is the achievable channel capacity, and B is the bandwidth. Our radio energy model assumes 1 Mbit/s capacity in the transceiver electronics. In the 2.4 GHz band, there are 16 ZigBee channels, with each channel requiring the bandwidth of 5 MHz. Therefore, $\beta = 0.149$.

2) Thermal Noise. This type of noise was first measured by Johnson[7]:

$$N = k_B T \Delta f \qquad (16)$$

where k_B is Boltzmann's constant in joules per Kelvin; T is the resistor's absolute temperature in Kelvins; Δf is the bandwidth in hertz over which the noise is measured. The resulting N is the thermal noise power in watts. Plugging in our experimentation parameters, we obtain the thermal noise at 9.7 pW, that is, −80.1 dBm.

3) Modeling of energy consumption under possible retransmission. To overcome the loss caused by simultaneous transmission, sensors have to retransmit the packet and, therefore, spend more energy.

Assuming that the re-try limit of each packet transmission is R_t, then

$$E_{\text{total}} = E_{\text{tx\_rx}} + E_{\text{re\_tx}} \qquad (17)$$

and

$$E_{\text{re\_tx}} = \sum_{k=1}^{R_t} k E_{\text{tx}} (1-p)^{k-1} p \qquad (18)$$

2.4 Analysis of cluster lifetime

Here we analyze the behavior of cluster rotation and see how energy is dissipated among all the sensors within a cluster.

First the upper bound of cluster lifetime is achieved if all nodes use their energy in the same manner. So the resulting lifetime is

$$T_{\text{ideal}} = \frac{nE_0}{E_{\text{total}}} \qquad (19)$$

where n is the average number of nodes in a cluster. Let $\boldsymbol{E}(t) = \{E_1(t), E_2(t), \ldots, E_n(t)\}^{\text{T}}$ denote the residual energy of all the nodes at time slot t. $\boldsymbol{A}(t) = \{0, 0, \ldots, 1, \ldots, 0\}$ is the vector that indicates which node is the current cluster-head. We calculate the energy distribution in each time slot t:

$$E_i(t+1) = E_i(t) - A_i(t)E_{\text{ch}} - [1 - A_i(t)]E_{\text{wk}} \quad i = 1, 2, \ldots, n_i \qquad (20)$$

Figs. 7 and 8 show the results of network lifetime with different routing techniques.

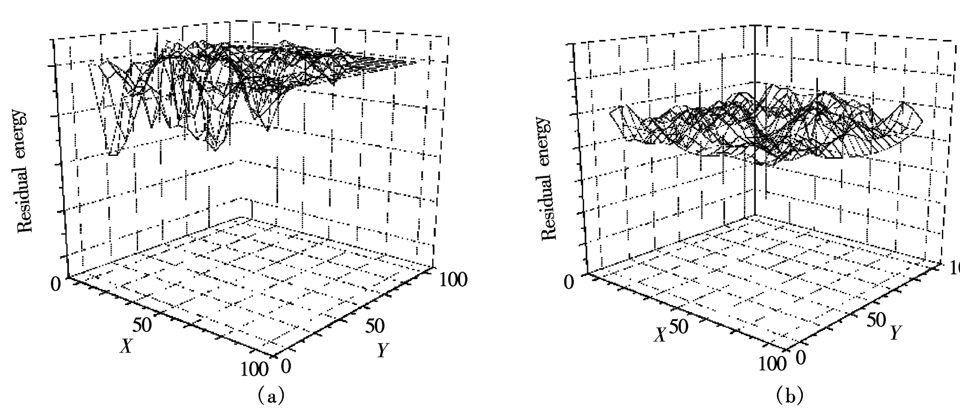

Fig. 7 Network lifetime with energy-aware routing. (a) After 30 s; (b) After 30 min

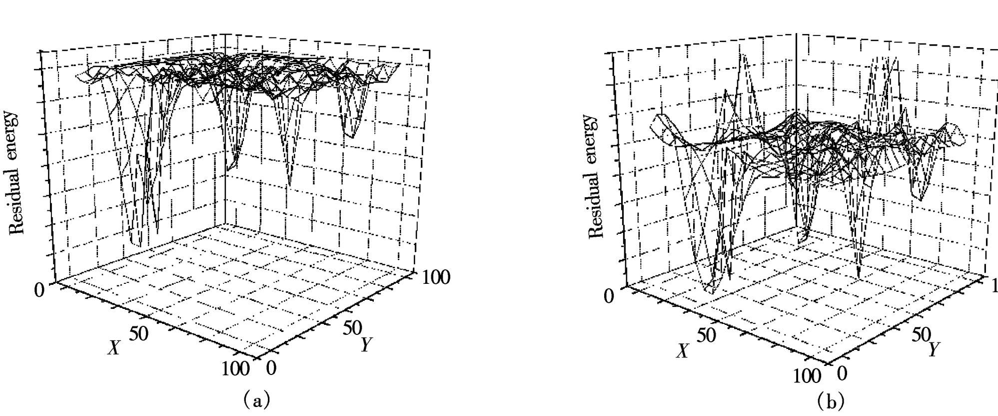

Fig. 8 Network lifetime with LEACH. (a) After 30 s; (b) After 30 min

3 Conclusion and Future Work

In this paper, we investigate energy-optimal grid-based clustering for sensor networks by modeling, analysis and simulation. Results show that there is an optimal grid size that leads to minimal energy consumption in a two-dimensional sensing field. Our work provides insights into the intrinsic limits of grid-based clustering schemes, and helps determine a better clustering strategy for energy efficiency.

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无线传感器网络中基于网格的能量感知路由协议

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摘要: 通过建立无线传感器网络环境中的能耗模型, 研究了高效能耗以及由路径损耗模型不同带来的数据干扰问题. 采用二维网格分簇机制, 其中簇头选举算法基于节点的剩余能量和随机退避时间, 以一种高效且分散的方式使簇头在所有传感器节点中均匀轮换. 节点除了在传输和接收数据过程中消耗能量, 在干扰重传时也需要消耗额外的能量. 根据平面几何学, 通过分析和数学推导, 得出网络的总能耗与分簇机制中的网格结构直接相关的结论, 其中簇的大小决定传输范围, 节点距离决定路径损耗指数, 网络结构决定同时传输数据的节点产生的干扰总数. 通过分析和仿真实验, 提出了在无线传感器网络中优化的网格结构和对应的网格大小, 从而在最大化降低能耗和最小化总体冲突之间达成平衡.

关键词: 无线传感器网络; 网格; 能量消耗; 干扰; 丢包

中图分类号: TP393