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A load-balanced minimum energy routing algorithm for Wireless Ad Hoc Sensor Networks

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Abstract: Wireless Ad Hoc Sensor Networks (WSNs) have received considerable academia research attention at present. The energy-constraint sensor nodes in WSNs operate on limited batteries, so it is a very important issue to use energy efficiently and reduce power consumption. To maximize the network lifetime, it is essential to prolong each individual node's lifetime through minimizing the transmission energy consumption, so that many minimum energy routing schemes for traditional mobile ad hoc network have been developed for this reason. This paper presents a novel minimum energy routing algorithm named Load-Balanced Minimum Energy Routing (LBMER) for WSNs considering both sensor nodes' energy consumption status and the sensor nodes' hierarchical congestion levels, which uses mixture of energy balance and traffic balance to solve the problem of "hot spots" of WSNs and avoid the situation of "hot spots" sensor nodes using their energy at much higher rate and die much faster than the other nodes. The path router established by LBMER will not be very congested and the traffic will be distributed evenly in the WSNs. Simulation results verified that the LBMER performance is better than that of Min-Hop routing and the existing minimum energy routing scheme MTPR (Total Transmission Power Routing).

Key words: Wireless Ad Hoc Sensor Networks (WSNs), Load-Balanced Minimum Energy Routing (LBMER)
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INTRODUCTION

Wireless Sensor Network is one special type of wireless ad hoc networks without fixed infrastructure consisting of a collection of sensor nodes, and operating on limited amount of battery energy consumed mostly in transmission and reception. In the WSNs described in Fig.1, every sensor node can sense, process data and communicate to base station (BS). WSNs have attracted much attention during the recent two years and some commercial implementations such as environmental surveillance applications are being developed because of their many advantages such as limited size, minimal memory and energy requirements and good computation ability, as well as their cheap and dense deployment compared to fixed infrastructure wireless networks and even traditional ad hoc networks. But the major problem of reducing sensor node energy consumption in WSNs has not been solved perfectly. If all sensor nodes transmit packets directly to the base station, the furthest nodes from the base station will die early. On the other hand, among sensor nodes transmitting packets through multiple hops, sensors closest to the base station tend to die early, leaving some network areas completely unmonitored and causing network partitions. In order to maximize the WSNs lifetime, it is essential to prolong each individual sensor node's lifetime by minimizing transmission energy consumption, and sending packets via paths that can avoid sensor nodes with low energy and minimizing the total transmission power.

To overcome the problem of energy-constraint in WSNs, many people have been working on different aspects such as power-aware MAC protocol, topology control, transmission power control, etc. In our work

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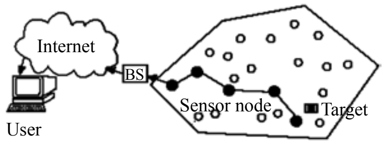

Fig.1 Wireless sensor networks

we save sensor nodes' energy mainly through energy-aware routing, which has received more and more attention in the recent few years.

As we know, Dijkstra's shortest path algorithm and Bellman-Ford's shortest path algorithm are not power-aware and do not work well for wireless networks, especially when one or more wireless nodes power off. Recently, several energy-aware multi-hop routing protocols for wireless ad hoc network have been proposed to minimize the total power over all the nodes. Minimum Total Transmission Power Routing (MTPR) protocol proposed by Dashy *et al*.(2002), sets the link cost to the transmission power and uses a shortest path algorithm to search for the minimum energy path. Minimum Total Transceiving Power (MTTCP) presented by Rodoplu and Meng (1998) assigns the transmission power as well as receiving power to the link cost metric. Singh *et al*.(1998) proposed Minimum Battery cost routing (MBCR) and Minimum Max Battery cost routing (MMBCR), using a battery cost function to decide route path. In Tohin (2001)'s Conditional MMBCR (CMMBCR), battery capacity instead of cost function is used as a route selection metric. CMMBCR relies on the residual battery capacity of nodes and considers both the total transmission energy consumption of routes and the remaining power of nodes. Minimum Total Reliable Transmission Power (MTRTP) proposed by Banerjee and Misra (2001) maintains that a link cost should be a function of both the energy required for a single transmission and the link error rate. A new routing algorithm for maximum network lifetime called max-min $zP_{\min}$ was studied by Li *et al*.(2001), who tried to strike a balance between the minimum transmission energy routing and the max-min residual energy routing.

WSNs have characteristics such as bandwidth-constraint, variable-capacity link and energy-constraint operations that will affect routing protocol design. A novel power-aware routing protocol named Load-Balanced Minimum Energy Routing (LBMER) is designed in this paper. The solution approach is based on reducing the energy consumption at routing discovery phase and establishing energy-saving routing paths. The LBMER protocol considers not only the major concern of reducing sensor node's energy consumption, but also the sensor node's congestion level.

MATHEMATICAL MODEL AND FORMULATION

In this paper, it is assumed that the sensor nodes are not mobile and that the topology of the WSNs is static or changes slowly enough such that there is enough time to balance the traffic. A wireless sensor network topology can be modeled by a weighted Bernoulli graph $G=(V,L,E)$, where V denotes the set of sensor nodes, L denotes the set of directional links (i,j) where $i, j\in\mathbb{N}$ and E denotes the set of the nodes' initial energy units. The transmitter power level of the sensor node is assumed to be adjusted to the minimum level appropriate for the intended receiver within the transmission range. It is assumed a $1/d^2$ path loss occurs in the sensor energy model by Bhardwaj *et al*.(2001) and Heinzelman *et al*.(2000), so the energy consumed is:

$$E_i^{\mathrm{tx}} = (e_i^{\mathrm{t}} + \varepsilon_{\mathrm{amp}} \times d^2) \times m, \quad E_i^{\mathrm{rx}} = e_i^{\mathrm{r}} \times m, \tag{1}$$

where E_i^{tx} is the energy to send m bits and E_i^{rx} is the energy consumed to receive m bits, $\varepsilon_{\mathrm{amp}}$ denotes the transmitter amplifier's energy consumption, e_i^{t} and e_i^{r} denote the transmission energy required by node i to transmit or receive an information unit (bit). In the simulation of this paper, these parameters are set as follows:

$$e_i^{\mathrm{t}} = e_i^{\mathrm{r}} = 50 \text{ nJ/bit}, \quad \varepsilon_{\mathrm{amp}} = 100 \text{ pJ/(bit}\cdot\text{m}^2). \tag{2}$$

The network's lifetime is defined as the time when any sensor node runs out of its own battery power for the first time because it can result in network partitioning and interrupt communication if a sensor node stops its operation.

Chang and Tassiulas (2000) proposed the lifetime formula of the wireless ad hoc network under a given flow is the time until the first battery drains out:

$$LifeTime = \min_{i \in V} \frac{E_i}{e_i \sum_{j \in N_i} f_{ij}}, \quad (3)$$

where N_i denotes the collection of its directional neighboring nodes for each node i, f_{ij} denotes the ratio between average flow on link (i,j) and the maximal possible flow on the link, e_i denotes the transmission energy required by node i to transmit an information unit.

We expand Eq.(3) for WSNs, the lifetime of WSNs is shown as follows:

$$LifeTime = \min_{i \in V} \frac{E_i}{E_i^{\text{tx}} \sum_{j \in N_i} f_{ij} + E_i^{\text{rx}} \sum_{i \in N_j} f_{ji}}, \quad (4)$$

where N_i and N_j denote the collection of its directional neighboring nodes for each node i and j, f_{ij} denotes the ratio between average flow from node i to node j and the maximal possible flow on the link, f_{ji} denotes the ratio between average flow from node j to node i and the maximal possible flow on the link.

Now the main issue of how to use energy efficiently can be expressed to maximize the lifetime of WSNs, as seen in Eq.(5). This is also called EER (energy efficient routing) problem.

$$\max(LifeTime) = \max\left(\min_{i \in V} \frac{E_i}{E_i^{\text{tx}} \sum_{j \in N_i} f_{ij} + E_i^{\text{rx}} \sum_{i \in N_j} f_{ji}} \right). \quad (5)$$

In the next section we will describe LBMER algorithms. Load-Balanced Minimum Energy Routing (LBMER) is a routing algorithm mainly considering a node's efficient energy consumption and MAC buffer queue length in order to avoid selected routing consisting of energy consuming nodes and prevent aggravation of nodes' congestion meanwhile.

LOAD-BALANCED MINIMUM ENERGY ROUTING SCHEME

A MAC buffer queue model is presented in Fig.2. P_i and P_o denote input and output of the MAC buffer queue, N denotes the total length of buffer queue and

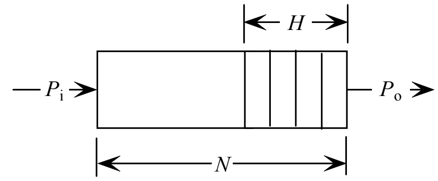

Fig.2 MAC buffer queue model

H denotes the current buffer length. It is supposed that input and output of buffer follow Poisson distribution with parameter λ and μ.

The probability of no overflowing of MAC buffer queue in time interval T is shown as:

$$P = P\{K_\lambda - K_\mu \le N - H\}, \quad (6)$$

where K_λ and K_μ denote the input and output packet length during the time T. Eq.(7) shows clearly the probability of no overflowing is decided by current buffer length H and maximum throughput of MAC layer S:

$$\begin{aligned} P &= \sum_{k_\mu=0}^{\infty} \sum_{k_\lambda=0}^{N-H+k_\mu} P\{k_\lambda \le N-H+K_\mu \mid K_\mu = k_\mu\} P\{K_\mu = k_\mu\} \\ &= \sum_{k_\mu=0}^{\infty} \frac{(\mu T)^{k_\mu}}{k_\mu !} \mathrm{e}^{-\frac{T_\mu}{2}} \sum_{k_\lambda=0}^{N-H+k_\mu} \frac{(\lambda T)^{k_\lambda}}{k_\lambda !} \mathrm{e}^{-\frac{T_\lambda}{2}} \\ &= \sum_{k_\mu=0}^{k_{\mu\max}} \frac{(\mu T)^{k_\mu}}{k_\mu !} \mathrm{e}^{-\frac{T_\mu}{2}} \sum_{k_\lambda=0}^{N-H+k_\mu} \frac{(\lambda T/2)^{k_\lambda}}{k_\lambda !} \mathrm{e}^{-\frac{T_\lambda}{2}}, \end{aligned} \quad (7)$$

where $k_{\mu\max}=S\times R_L\times T$, R_L denotes the speed of MAC dealing with network packets and S denotes the maximum throughout of MAC layer. So we think the MAC buffer queue length can be used as the metric to measure sensor nodes' traffic congestion levels.

Let Q_i and $Q_{i\text{avg}}$ denote the current and average MAC queue buffer length, $Q_{i\max}$ and $Q_{i\min}$ denote the maximum and minimum MAC buffer length threshold. The buffer queue occupancy ratio B_i is shown as Eq.(8).

$$B_i = \begin{cases} 1 & (Q_{i\text{avg}} < Q_{i\min}), \\ \dfrac{10\times(Q_{i\text{avg}} - Q_{i\min})}{Q_{i\max} - Q_{i\min}} + 1 = \dfrac{10\times(Q_{i\text{avg}} - Q_{i\min})}{Q_{i\max} - Q_{i\min}} + 1 & (Q_{i\min} \le Q_{i\text{avg}} < Q_{i\max}), \\ 11 & (Q_{i\text{avg}} \ge Q_{i\max}). \end{cases} \quad (8)$$

The average queue length $Q_{i\text{avg}}$ updates itself by the exponential weighted moving average (EWMA) algorithm and we set ω=0.002 in the following simulation:

$$Q_{i\text{avg}} = (1-\omega)Q_{i\text{avg}} + \omega Q_i \,. \tag{9}$$

Following the idea of Battery Cost Function f_i proposed by Kim *et al*.(2002) and Tohin (2001), Battery Cost Function is redefined for sensor node i. The Battery Cost Function f_i proposed in this paper denotes the ratio of battery energy usage and battery residual energy: $f_i=(E_i-R_i)/R_i$, where $R_i\neq 0$ denotes residual battery energy capacity and E_i denotes total battery energy capacity. The LBMER algorithm is explained below.

Let ith node's Cost Function C_i be the product of battery cost function and buffer queue occupancy ratio function:

$$C_i = f_i \times B_i = \begin{cases} f_i \times 1 = \dfrac{E_i - R_i}{R_i} & (Q_{i\text{avg}} < Q_{i\min}), \\ \dfrac{E_i - R_i}{R_i} \times \left(\dfrac{10 \times (Q_{i\text{avg}} - Q_{i\min})}{Q_{i\max} - Q_{i\min}} + 1 \right) & (Q_{i\min} \le Q_{i\text{avg}} < Q_{i\max}), \\ f_i \times 11 = \dfrac{E_i - R_i}{R_i} \times 11 & (Q_{i\text{avg}} \ge Q_{i\max}). \end{cases} \tag{10}$$

From Eq.(10) we can find that the node's cost function C_i degenerates to Minimum Energy Routing and does not consider buffer occupancy ratio when $Q_{i\text{avg}}<Q_{i\min}$ or $Q_{i\text{avg}}\ge Q_{i\max}$. This is also a kind of QoS routing and QoS weights are queue buffer occupancy ratio and battery residual ratio.

The total cost of route R_j is:

$$M(R_j) = \sum_{i=0}^{n-1} C_i \,. \tag{11}$$

Finally the best route R_{best} is:

$$M(R_{\text{best}}) = \min_{R_j \in R^*} \{M(R_j)\} \,, \tag{12}$$

where R^* is the collection of all paths from source to the destination.

Eqs.(8)~(12) clearly implies that $M(R_j)$ is large if either the sensor node's buffer length occupancy is high or sensor node's battery energy usage is high. So the LBMER algorithm considers not only sensor node's energy efficient consumption but also the sensor node's buffer length occupancy levels. Furthermore, we introduce the maximum buffer length threshold and minimum buffer length threshold to indicate the sensor node's congestion level. If $Q_{i\text{avg}}$ is smaller than $Q_{i\min}$, the sensor node i can be considered not congested and let C_i equal to f_i; else when $Q_{i\text{avg}}$ is greater than $Q_{i\max}$, the ith sensor node is considered heavily congested and let C_i equal to $11\times f_i$; when $Q_{i\text{avg}}$ is between $Q_{i\min}$ and $Q_{i\max}$, the ith sensor node's cost function C_i is a linear function of queue buffer length. As a result, the selected best routing is the minimum cost of all routes.

SIMULATION RESULTS

In this section, we evaluate the proposed load-balanced minimum energy routing scheme and compare it with Min-Hop routing and MTPR via simulations. The network's normalized lifetime, throughput and transmission delay are measured as three key metrics.

In this set of simulations, scene area is set as 100 m×100 m, the number of total sensor nodes is 200. The initial energy of all sensor nodes is E_i=10 J. The maximum value of MAC buffer size equals to 256 kb. Base station is located at (50,50). In the simulation, the total process consists of 10 rounds in every round random 20 sensor nodes send packets to the base station with every packet size equaling 1024 bits. In addition, sensor nodes generate traffic at a rate $R_g(r)$ packets/s following Poisson distribution with parameter r and network load level is changed by changing parameter r. LBMER parameters are set as $Q_{i\min}$=50 kb and $Q_{i\max}$=150 kb for all the sensor nodes.

We evaluate the proposed algorithm by comparing the network normalized lifetime. Network normalized lifetime is the ratio between the lifetime of Min-Hop and LBMER, MTPR and LBMER, LBMER and LBMER. So the network normalized lifetime of LBMER equals to 1 all the time. Obtained by repeated simulations and statistical analysis, the results shown in Fig.3 indicate that LBMER exceeds Min-Hop and MTPR in average normalized lifetime especially when meeting much heavier traffic (larger *r*).

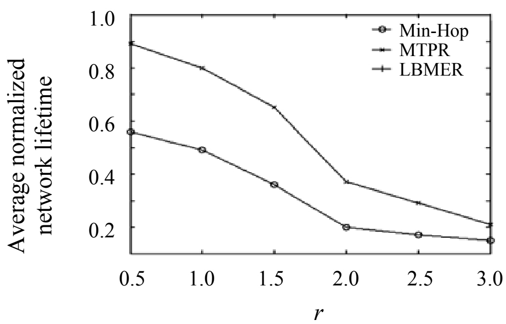

Fig.3 Average normalized network lifetime versus *r*

The simulation results in Figs.4 and 5 showed differences of throughput and transmission delay between Min-Hop, MTPR and LBMER. It is clear that with LBMER the network performance, mainly including average throughput and average delay, is much better than that of Min-Hop or MTPR because LBMER will relieve sensor node with heavy load, expressed by large buffer occupancy and large usage ratio of battery energy. As a result transmission delay is reduced, network throughout is increased and the lifetime of WSNs is prolonged. As a result, the results shown in Figs.4 and 5 prove that LBMER is evidently much better than Min-Hop and MTPR as the respect of energy efficiency and network traffic congestion control.

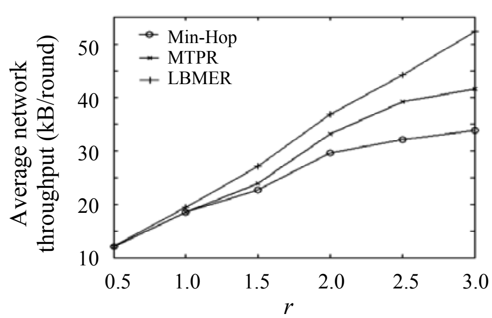

Fig.4 Average network throughput versus *r*

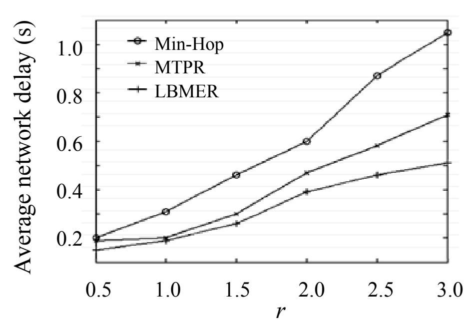

Fig.5 Average network delay versus *r*

CONCLUSION

In this paper, a novel Load-Balanced minimum energy routing scheme for WSNs, which selects routing according minimal energy consumption and MAC buffer length, is presented and simulated. The simulation results obviously indicated that much better traffic balance effect and maximum network lifetime could be achieved with the presented scheme. In future, the LBMER algorithm with constrained buffer length occupancy ratio and battery residual ratio would be studied further as a MCOP (Multi-Constrained Optimal Path) problem.

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