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An Adaptive Energy-aware Multi-path Routing Protocol with Load Balance for Wireless Sensor Networks

Ming Tao · Dingzhu Lu · Junlong Yang

Abstract Using the available but limited resources of sensors more efficiently has been the recent interest in designing the routing protocols for Wireless Sensor Network (WSN). The major concern includes energy, storage and computing resources. Accordingly, we propose an adaptive energy-aware Multi-path routing protocol with load balance (AEMRP-LB). It introduces a concept named direction-angle to overcome the deficiency of broadcast and takes into account the tradeoff between the residual energy and hop count to establish multiple node-disjoint paths. The traffic load is balanced over the selected paths by using a weighted traffic scheduling algorithm considering their transmitting capacity, and then AEMRP-LB uses the advantages of Multi-path Source Routing to report the acquired data as saving the computing and storage resources of the sensors. In the scene with multiple Source-Sink pairs, AEMRP-LB can adaptively adjust the available residual energy of shared nodes so as to make reasonable use of them. The simulation results show that AEMRP-LB outperforms the two comparative schemes, and the sensors consume the energy in a more equitable way which ensures a more graceful degradation of service with time.

Keywords WSN · Multi-path · Energy-aware · Node-disjoint · Load balance · Adaptively

1 Introduction

Wireless Sensor Networks [1,2] typically refer to large ensemble of inter-connected nodes. These nodes should be equipped with processing and communication capabilities, and one or more sensing devices. The deployment of such network is usually done in ad-hoc manner

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M. Tao (✉) · D. Lu · J. Yang
School of Computer Science and Engineering, South China University of Technology,
510006 Guangzhou, China
e-mail: ming.tao@mail.scut.edu.cn

D. Lu
e-mail: ludingzhu@gmail.com

J. Yang
e-mail: junlong.yang@mail.scut.edu.cn

(e.g., dropping sensors from an aircraft on the field) which implies that the sensors need to self-organize into a multi-hop wireless ad-hoc network. The prime purpose of such sensor network is gathering the information of environments or the objects they are sensing and send the information back to end-users. In recent years, there has been a rapid development in building and deploying sensor networks which is promoted by the recent advances in MEMS-based technologies and low-power short-range radios. In addition, as the hardware for sensors has become increasingly more affordable and widely available, sensor networks have emerged as an ideal solution to a number of important potential applications include civilian scenarios in food and safety industries and environmental monitoring, military scenarios for the digital battle field and security services.

Designing routing protocols for WSN is influenced by many factors, such as hardware restrictions, energy consumption and network topology. Many large-scale sensor networks consist of battery-powered sensors whose battery unit may not be replaceable, they usually adopt the multi-hop communication mode to avoid the source node having a high transmitting power and the limited energy unit being depleted too soon. The restrained storage and computing resource also make the sensors store mass of routing information and calculate complicated routing impossible. Indeed, a major challenge facing the development and deployment of large-scale sensor networks is the scheduling of transmissions among nodes in the fashion of (1) automatically adapting to the changes in traffic, node state and connectivity; and (2) prolonging the battery lifespan of each node.

Accordingly, we take into account the limited energy, storage and computing resources, and propose an adaptive energy-aware Multi-path routing protocol with load balance (AEMRP-LB) for Wireless Sensor Networks in this paper. The main contributions made in this paper are stated as follows:

1. A concept named direction-angle is introduced to overcome the deficiency of broadcast and multiple node-disjoint paths are established by taking into account the tradeoff between the hop count and the residual energy and they provide a reliable data delivery. A weighted traffic scheduling algorithm considering the transmitting capacity of the selected paths is used to assign the traffic load over these paths in balance. The advantages of MSR is used to report the acquired data as saving the storage and computing resources for sensors.
2. In the scene with multiple Source-Sink pairs, AEMRP-LB can adaptively adjust the available residual energy of shared nodes so as to make use of them reasonably and make them provide different qualities of services for the Interests with different importance.
3. A series of well-designed experiments are undertaken to compare AEMRP-LB with MERP [19] and Direct Diffusion [23]. The simulation results show that AEMRP-LB has higher node energy efficiency and lower communication interruption delay than the two other protocols.

The remainder of this paper is organized as follows: Sect. 2 provides a brief overview of related works. Section 3 addresses the basic idea of AEMRP-LB. The simulation setup and performance comparison are described in Sect. 4. Finally, we summarize and conclude this paper in Sect. 5.

2 Related Works

This section describes some related works dedicated by other experts previously, which have led to the contributions described in this paper.

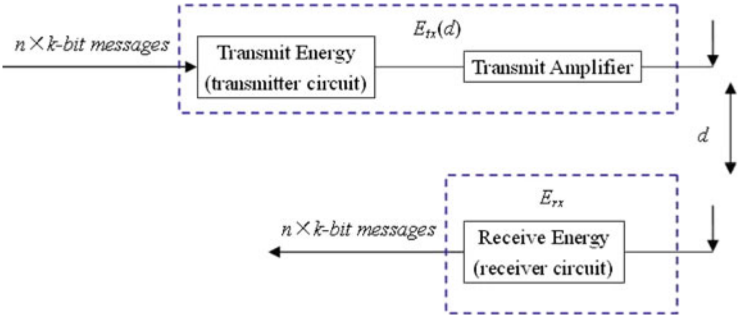


Fig. 1 The radio model of transmitting *n* messages

2.1 The Analysis of Radio Model and Two Routing Protocols

Currently, an extensive body of research has focused on the area of low-energy radios. Different assumptions about the radio characteristics, including energy dissipation in the data transmitting, receiving and fusion pattern, will change the advantages of different protocols [3]. Figure 1 describes the radio model of transmitting n messages and the size of each message is $k - bit$, so the total amount of transmitting messages is $n \times k$ $bits$.

Communication is a prime factor of energy dissipation for the sensors in WSN, therefore, we focus on the communication-related activities of the sensors which use battery as their energy supplier [3]. We assume that each sensor within the network has the same data transmitting rate denoted by r, so the minimal energy dissipation of transmitting messages with the total amount of $n \times k$ $bits$ at rate r over the Euclid distance d is formulated in (1). In some scenes, the relay nodes may receive some messages of the same data type, so the sensors must be equipped with the ability of data fusion in order to reduce the transmission of redundancy data, and data fusion also leads to some energy dissipation, while we do not touch on this in the radio model.

$$E_{tx}(n, k, r, d) = nkr\varphi_1 + nkr\varphi_2 d^{\alpha} \tag{1}$$

where, φ_1 is a distance-irrelevant factor, such as the energy dissipation in the transmitter circuit. φ_2 is a distance-related factor, which mainly considers the more complicated scenes with the influence of geographical shadowing. An exponent α is also introduced to denote the path loss whose value usually falls into the range of [2,4], for example, $\alpha = 2$ for free space and $\alpha = 4$ for multi-path fading. The value of α is set as 2 in this paper.

For all sensor nodes, the energy dissipation of receiving $n \times k$ $bits$ messages at rate r mainly focuses on the dissipation in the receiver circuit which is distance-irrelevant. For the sake of simplicity, we assume that the transmitter circuit and the receiver circuit have the same energy dissipation, just as shown in (2).

$$E_{rx}(n, k, r) = nkr\varphi_1 \tag{2}$$

Therefore, the total communication-related energy dissipation of relaying $n \times k$ $bits$ messages at rate r over distance d at $i -$ th node is shown in (3).

$$\begin{aligned} E_{i-node} &= E_{tx}(n, k, r, d) + E_{rx}(n, k, r) \\ &= nkr(2\varphi_1 + \varphi_2 d^{\alpha}) \end{aligned} \tag{3}$$

Because the total communication-related energy dissipation for source nodes mainly falls on the transmitting dissipation, the energy dissipation is just shown in (1).

We assume that the initial energy allocated for $i-$ th relay node is denoted as e_{i-node}. With the linear energy dissipation model, the lifespan of $i-$ th node which is denoted as l_{i-node} is defined in (4), in which t_0 is the initial time of the system.

$$\int\limits_{t=t_0}^{t_0+l_{i-node}} E_{i-node}(t)dt = e_{i-node} \tag{4}$$

On the basis of the radio model stated above, we analyze two protocols: direct communication and the minimum-energy multi-hop routing.

Direct communication, just as the name implies, it requires the Source sends its data directly to the Sink. This protocol may be an optimal communication mode in the scene that the Source is very close to the Sink. However, if the Sink is far away from the Source, a large transmitting power for the Source is required to ensure the Sink to be located in its radio coverage area. It will quickly deplete the energy of battery and decreases the system lifespan.

In minimum-energy multi-hop routing protocols, the Source transmits data towards the Sink through intermediate nodes which act as routers. These protocols differ in the way of choosing routings. We assume that node A wants to transmit data to node C. If and only if the situation shown in (5) or (6) is met, node A would transmit packets to node C though node B [4], E_{tx-amp} denotes the energy dissipation of the Transmit Amplifier.

$$\begin{aligned} &E_{tx-amp}(n,k,r,d=d_{AB}) + E_{tx-amp}(n,k,r,d=d_{BC}) \\ &\quad < E_{tx-amp}(n,k,r,d=d_{AC}) \qquad (5) \\ &\quad \text{Or} \qquad d_{AB}^2 + d_{BC}^2 < d_{AC} \qquad (6) \end{aligned}$$

The system may consume less energy by using multi-hop routing as opposed to using direct communication, since $E_{tx}(n,k,r,d)$ increases exponentially with distance d. However, if the message is relayed too many times, it may dissipate even more energy. In order to illustrate the energy dissipation of direct communication and multi-hop routing, we assume that the Source wants to transmit $n \times k$ *bits* messages to the Sink. There are $m-2$ intermediate nodes between the Source and the Sink and they are placed in a linear format; the distance between the adjacent nodes is l, so the distance from the Source to the Sink is $(m-1)\times l$. According to the adopted energy model stated above, we can deduce the energy dissipation of the two different protocols.

Since the direct communication approach requires the Source to send packets to the Sink directly, we can get the energy dissipation E_{direct}, which is shown in (7).

$$E_{direct} = E_{tx}(n,k,r,d=(m-1)\times l) = nkr\{\varphi_1+\varphi_2[(m-1)\times l]^2\} \tag{7}$$

In multi-hop routing, each node sends the packet to the neighbor node along the way to the Sink, so the Source locates a distance $(m-1)\times l$ from the Sink would require $m-1$ times of transmitting with a distance of l and $m-1$ times of receiving. The deduced energy dissipation $E_{multi-hop}$ is shown in (9), without considering the fusion dissipation.

$$\begin{aligned} E_{multi-hop} &= (m-1)\times E_{tx}(n,k,r,d=l) + (m-1)\times E_{rx}(n,k,r) \\ &= (m-1)nkr(\varphi_1+\varphi_2 l^2) + (m-1)nkr\varphi_1 \\ &= nkr(m-1)(2\varphi_1+\varphi_2 l^2) \end{aligned} \tag{8}$$

If $\frac{\varphi_2}{\varphi_1} > \frac{2m-3}{(m^2-3m+2)l^2}$, we can get a conclusion that the multi-hop routing dissipates less energy than direct communication by comparing (7) and (8).

According to the analysis of the radio mode and the comparison of the two routing protocols, we come to a conclusion that the transmitting dissipation is the prime part of the total energy consumption, while the dissipated energy of receiving data also should not be ignored. We should minimize the transmitting distances, the number of transmitting and receiving operations, the total amount of sending data and the number of forwarding nodes to reduce energy consumption.

2.2 Related Routing Protocols

There are several performance criteria for comparing single-path routing and multi-path routing in Wireless Sensor Networks. In multi-path routing, the overhead of route discovery is much more than that in single-path routing, but the frequency of route discovery is much less because of the traffic still being operated by some valid paths between the Source and the Sink even if one or a few of the paths fail. Besides, assuming that the capacities such as bandwidth and processing energy of all the nodes are fixed and limited, the overall throughput would be higher owing to using multi-paths routing which results in a better balancing of load throughout the network. Moreover, fault tolerance or robustness is an inherent feature of multi-path routing [5]. The existing multi-path protocols typically employ an on-demand routing approach to search for paths. The source node broadcasts a routing request message into the network, and the IDs of the visited intermediate nodes are appended into the messages. The destination node then sends reply messages to the source node along the reverse paths. However, broadcast is a wasteful approach of routing discovery, we introduce a concept named direction-angle and use it to forward the message in the right direction towards the Source without using broadcast in this paper. Multi-paths are generally categorized into node-disjoint ones and link-disjoint ones (or called braided paths). Node-disjoint multi-path routing tries to establish alternate paths that are node-disjoint with the primary path and node-disjoint with each other, thus, the system is immune to the failure of the primary path. Link-disjoint multi-path routing relaxes the requirement that node-disjoint multi-path routing equipped with, it allows the alternate paths in a braid to share some common nodes with the primary path, so the paths are not completely node-disjoint and the traffic congestion would be happened on the shared common nodes. Hence, the node-disjoint multi-path routing protocol can support efficient and reliable data transmission. Literature [6] aims to find node-disjoint multi-paths, whereas [7] considers link-disjoint multi-paths. Literatures [8] and [9] considers both kinds of multi-paths. The authors in [9] assume that the network topology is known for each node. k minimum energy node-disjoint and link-disjoint paths are calculated by executing a minimum weight k node-disjoint paths algorithm.

In recent years, aiming at the restrained energy problem, WSN has sparked numerous research interests in Multi-path routing algorithms. By reducing the frequency of route discovery, the multi-path routing protocols are employed to improve the energy efficiency. The authors of [10] introduce a new multiple paths routing protocol named Multi-path Souring Routing (MSR), it is based on Dynamic Souring Routing (DSR) and inherits all the advantages of DSR. The advantages just meet the requirements of designing the routing protocols for Wireless Sensor Networks which are constrained by energy and memory resources. AEMRP-LB proposed in this paper utilizes the advantages of MSR to report the acquired data. In [11] and [12], similar ideas used multi-path are introduced to extend the DSR and AODV (Ad hoc On-demand Distance Vector) to improve the energy efficiency in Ad hoc networks. Multi-path can also provide reliability for transmitting information and most multi-path routing protocols take the network reliability as the chief designing objective. In [13], the authors design a reliable disjoint and braided multi-path routing protocol based on network coding (NC-RMR), it forms multiple paths by hop-by-hop method, each local node divides its neighbors into groups according to their hops to the Sink and selected its own backup neighbors to form braided multi-path. The authors in [14] present a routing protocol named MMSPEED. It is designed for probabilistic QoS guarantee from two aspects: timeliness and reliability. The former is provided by guaranteeing multiple packet delivery speed options, while the latter is supported by probabilistic multi-path forwarding. Literature [15] also utilizes the multiple paths between the Source and Sink pairs for providing soft-QoS for different packets as path information is not readily available.

Some routing protocols focus on network survivability. The authors of [16] present a uniform balancing energy routing protocol, it chooses the nodes whose residual energies were greater than a threshold as routers for other nodes in every transmission round, and distributes the energy load among any sensors to maximize the whole network lifetime. By performing a detailed tradeoff analysis of the influencing factors about the energy consumption, literature [17] presents an optimization algorithm for minimizing the overall energy consumption of the hardware and the physical link. Some routing protocols take into account both the energy-efficient and load balancing. Lu et al. in [18] propose an Energy-Efficient Multi-path Routing Protocol (EEMRP). It has the capability of searching multiple node-disjoint paths and utilizes a load balancing method to assign the traffic over each selected path. Both the node residual energy level and hop count are considered to introduce the link cost function. It uses a fairness index to evaluate the level of load balancing over different multi-paths. Furthermore, since EEMRP only takes care of data transfer delay, the reliability of successful paths is poor. Kim et al. in [19] develop a Multi-path Energy-aware Routing Protocol (MERP) which only uses the localized information to find node-disjoint paths and takes into account the network reliability. It arrays the paths according to the probability of successfully delivering a message to the Sink and introduces a load balancing scheme to adjust traffic flows. However, it requires each sensor to maintain the information of neighbor nodes, which means the storage overhead of each sensor is increased. FML-MP (the fuzzy multi-path maximum lifespan routing scheme), an online multi-path routing scheme which strives to achieve a good distribution of the traffic load, is developed in [20]. It uses an edge-weight function designed by using a fuzzy membership function in the path search process.

Most routing protocols in Wireless Sensor Network also use an optimal single path selected based on different metrics of transmitting data. The scheme proposed in [21] selects optimal path based on the node residual energy level. The authors in [22] present a single-path routing algorithm, it initially obtains a multi-path solution by using a multi-path LP formulation, on the basis of the result processed by an approximation algorithm, it then obtains single-path routing. Directed Diffusion [23] is the representative scheme of reactive protocols based on flooding and uses the gradient of information to select optimal path. It introduces four concepts including Interest, gradient, data transmission, and reinforcement. A probing task is propagated throughout the network as an Interest which is defined as a list of attribute-value pairs. If the acquired data matches the Interest, the Source sets up probing gradients along multiple paths within the network designed to draw events. Events begin by flowing towards the originators of Interests along these probing gradients. Subsequently, the system reinforces either one or a small number of these paths with the maximal gradient. The reinforced path with the maximal gradient is also the path with the least energy dissipation. Direct Diffusion always selects the reinforced path to transmit data, so the total network lifespan may be short.

3 An Adaptive Energy-aware Multi-path Routing Protocol with Load Balance

The potential problem in some current protocols such as Direct Diffusion is that they find the lowest-energy-cost path to optimize energy usage at the nodes along the routing and frequently use the path for reporting data gathered by the tasks such as temperature and humidity probing. However, from the network lifespan and long-term connectivity standpoint, frequently using the lowest-energy-cost paths may not be optimal, because it leads to excessive energy depletion of the nodes along the path and may cause network partition.

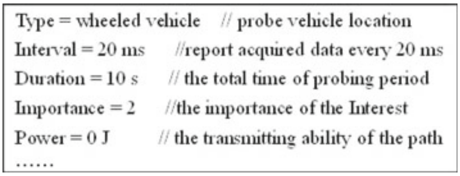
To address this issue, we propose an adaptive energy-aware multi-path routing protocol with load balance (AEMRP-LB) which focuses on prolonging the network lifespan. The basic idea is divided into two aspects:

1. In the scene with one Source-Sink pair, AEMRP-LB establishes multiple node-disjoint paths which are hop count and residual energy tradeoff and balances the traffic load over the selected multiple paths by using a weighted traffic scheduling algorithm considering their transmitting capacity. It ensures the energy dissipation to be evenly distributed in the whole network and the network service as a whole degrades gracefully with time rather than getting partitioned.
2. In the scene with multiple Source-Sink pairs, the selected paths belong to different Source-Sink pairs will have some shared nodes inevitably. In order to use the shared nodes reasonably and make them provide different qualities of services for the Interests with different importance, AEMRP-LB also can adaptively adjust the available residual energy of the shared nodes in terms of the importance of the passing Interest, and then uses the approach described in the first aspect to establish paths for each Source-Sink pair.

For the sake of argument, we assume that there are three types of nodes in Wireless Sensor Networks: Sink, regular sensor nodes and Source. They may have different architecture and function. For simplicity, we assume that the Sink is not energy-constrained, the Source will not be burned-out in the probing duration, and all the nodes within the network have the same transmitting power, they will consume the same energy to send or receive a packet. The communication is bi-directional and symmetric and the energy dissipation of transmitting a packet from node A to node B is equal to that from B to A. The potential packet collision can be effectively eliminated by setting a random delay before forwarding for every node.

Most of the probing tasks in sensor networks are data-oriented query requests. We also name the probing task as an Interest just as that defined in Directed Diffusion [23] and extend the definition by adding two attribute-value pairs, one is named *power-value* representing the transmitting capacity of the path that the Interest passed, the initial value of *Power* is zero. The other one is named *Importance-value* representing the importance of the passing Interest. Because the objective of each probing Interest is definite, we can preset the value of *Importance* accordingly. If the value of *Importance* of an Interest is more than a threshold, we believe that the Interest is important, otherwise, it is unimportant. The threshold is given by the average of the values of *Importance* of all Interests being about to be deployed in the scene plus a standard deviation. The simple description of a vehicle tracking task is shown in Fig. 2. The acquired data in response to Interests are also named using the similar naming scheme defined in Direct Diffusion.

Fig. 2 An example of probing task



Type = wheeled vehicle // probe vehicle location
Interval = 20 ms //report acquired data every 20 ms
Duration = 10 s // the total time of probing period
Importance = 2 //the importance of the Interest
Power = 0 J // the transmitting ability of the path
……

3.1 Establish the Routings

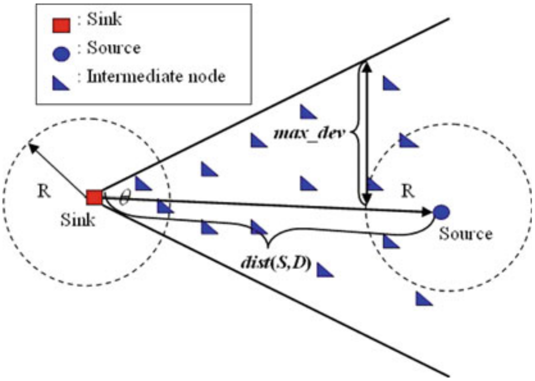
3.1.1 The Routing Establishing Process in the Scene with One Source-Sink Pair

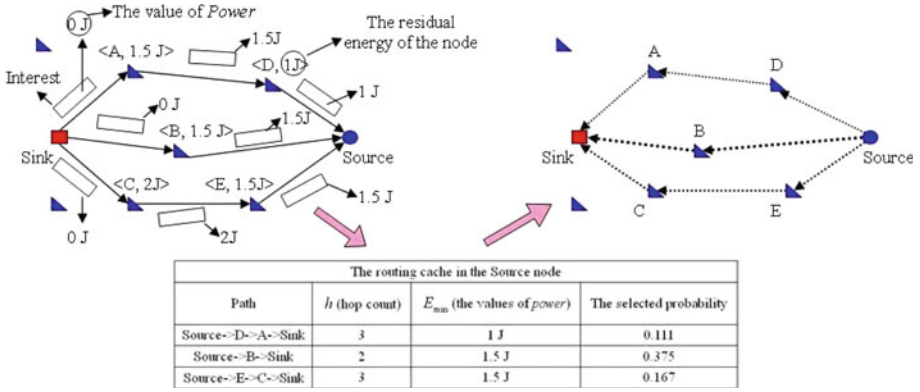
The Sink checks its routing table before it struggles a probing Interest. If there is not a routing destined to the Source in the table, the Sink will launch a process of route discovery. Before describing the routing establishing process, we introduce some related knowledge. So long as we know, broadcast is a wasteful approach of route discovery, if we omni-directionally broadcast the Interest, the nodes which are not in the right direction or may be in the just opposite direction can establish some paths, however, these paths are not acceptable because of the hop counts are too large. Hence, the geographic information of the sensors in the scene is very useful for establishing the routings, since it can make the Sink communicate with the Source in the right direction. Given this idea, we introduce a concept named direction-angle [24] in order to make the Sink and the interested intermediate nodes send the Interest to those next hops which are in the right direction towards Source. In particular, when the relay nodes have been within the radio coverage area of the Source, they should directly propagate the Interest towards the Source without using direction-angle again, otherwise, there would be much more forwarding nodes and some unnecessary overheads and resources waste are brought about. The cost of calculating direction-angle at interested relay nodes can not be ignored, but it is much less than the excessive overhead caused by broadcast. The number of optional next hops may be reduced by using the direction-angle, so properly setup the value of the direction-angle to avoid over-constraining is also very important. When the relay node is far away from the Source, the direction-angle should be small to restrict the next hops which are not in the right direction to be chosen, while the relay node is near to the Source, the direction-angle can be relatively large since the optional next hops will not deviate much from the Source in short distance. In this paper, a formula for calculating the direction-angle is defined in (9). In the scene with multiple Source-Sink pairs, the detectors are geographically-scattered, so the direction-angle can make the nodes in a particular direction provide more independent resources for a detector, and effectively avoid the energy hole being appeared early.

$$\frac{\theta}{2} = \arctan\left(\frac{max\_dev}{|dist(S, D) - R|}\right) (\theta \leq \pi) \tag{9}$$

where, $dist(S, D)$ denotes the distance between S (the source) and D (the Destination), R represents the radius of the radio coverage area. The sensor can receive data once the radio signal reaches into its radio coverage area. max_dev represents the maximum projected deviation from the Source. From the definition in (9), we can see that the configuration of max_dev has a great impact on the value of the direction-angle, if the configuration is too small, the direction-angle would be so extremely tightly constrained that the number of optional next hops would be reduced, while if the configuration is too large, some next hops are not in the right direction towards the Source would be chosen and it leads to some

Fig. 3 The sketch of direction-angle





The routing cache in the Source node			
Path	h (hop count)	E_{min} (the values of *power*)	The selected probability
Source->D->A->Sink	3	1 J	0.111
Source->B->Sink	2	1.5 J	0.375
Source->E->C->Sink	3	1.5 J	0.167

Fig. 4 The establishing process of energy-aware multi-path routing

resource waste. In this paper, the value of max_dev is defined as half of that of $dist(S, D)$ in empirical analysis. A sketch of direction-angle is shown in Fig. 3.

The Sink sends the Interest to its neighbors in the right direction by using direction-angle, and the first reached intermediate nodes append the values of their residual energy into the *power-value* pair in the Interest, and then transmit the updated Interest to their respective neighbors in the right direction. If the value of the residual energy of the currently reached node is less than that registered in the Interest, the value of the attribute *power* is updated, otherwise, the value should not be updated. The Interest from the Sink now is derived into several different Interests forwarded along different paths, their *power-value* pair is the only difference. When these Interests along different paths reach the Source, the values of *power* in different Interests determine the transmitting capacity of these paths. From another perspective, the information of *power-value* represents the maximum lifespan of the path. Because the intermediate nodes consume the same energy to forward a packet, the maximum lifespan of the path is determined by the node with minimum residual energy in the path. Figure 4 shows the routing establishing process, in which the node is labeled by its name and the value of residual energy.

After discovering the routings, there are many candidate-paths stored in the routing cache of the Source. The Source can obtain these information, such as the hop counts (h) and the values of *power* ($E_{\min}$) of different paths, it can calculate the selected probability p by using (10) for all cached candidate-paths, and then sorts the selected probabilities in a descending order. The path with a large hop count is not optimal, while with a large value of *power* is more acceptable in terms of the analysis. That is to say, the selected probability is proportional to the value of *power* and in inverse proportion to the hop counts, so we set $\beta = -2$ and $\gamma = 1$ in this paper.

$$p = h^{\beta} E_{\min}^{\gamma} \quad (\beta < 0, \gamma > 0) \tag{10}$$

We introduce two thresholds $thresh\_1$ and $thresh\_2$ ($thresh\_1 > thresh\_2$) to preprocess all candidate-paths in the routing cache. We set the path whose probability is more than $thresh\_1$ as a preferred path, the path whose probability falls into the range of $thresh\_2 \sim thresh\_1$ is set as a backup path, and the path with the probability less than $thresh\_2$ is dropped. We employ the following approach to define the two thresholds: because the selected probabilities of the candidate paths established for different Interests have the same distribution, we firstly select a set of candidate paths sorted in a descending way as the sample, and then use the algorithm of K-means ($K = 3$) to cluster these paths. The original sample now has been divided into three clusters. We can directly use K-means to cluster the candidate paths stored in the routing cache, and the overhead of online process is not considerable because of the data to be handled is one-dimensional, but we address the need of saving the overhead of the Source and still offline operate the process. We respectively pick out two smallest selected probabilities from the two clusters with bigger selected probability, and then respectively calculate the ratios between the two probabilities and the biggest probability in the original sample. For each Interest, $thresh\_1$ and $thresh\_2$ are respectively defined as the products of the radios and the biggest selected probability. Comparatively speaking, this method has less overhead than that of directly using K-means to cluster the candidate paths. After being preprocessed, the complexity of the following operating steps for the candidate paths is reduced.

Considering the case that a node in one path established for an Interest may belong to other paths established for different Interests, in order to reserve some transmitting capacity for other Interests, the node should not be the relay node belongs to several paths for the same Interest simultaneously. In order to achieve this target, we adopt the node-disjoint and classification idea to dispose the candidate paths of the same Interest. The node-disjoint paths are preferred because a more independent path can provide more resources between the Source and the Sink. According to the sorted result of the selected probability, we pick out a path with the largest selected probability as the most optimal path, and then choose the sub-optimal paths which are node-disjoint with the former-optimal paths. In the case that there are two or more sub-paths having the same selected probability and sharing none of common intermediate nodes, they will all be selected as the optimal paths for the current level, otherwise, if they have the same selected probability and share some common intermediate nodes, we should compare the total energy dissipation among these paths to decide to choose which path for the current level. According to the assumptions in this paper, the total energy dissipation of a path is determined by its hop count. AEMRP-LB requires both inter-levels and intra-levels paths to be node-disjoint. The node-disjoint and classification process is just like constructing a resembled graph shown in Fig. 5, where, the vertex represents the candidate path, and the edge between every vertex shows the two paths are node-disjoint with each other. The root is the path with largest selected probability.

3.1.2 The Routing Establishing Process in the Scene with Multiple Source-Sink Pairs

In the practical scenarios, the relay sensors for different Interests may be deployed dispersedly so that the number of the shared nodes along the established paths may be small. However,

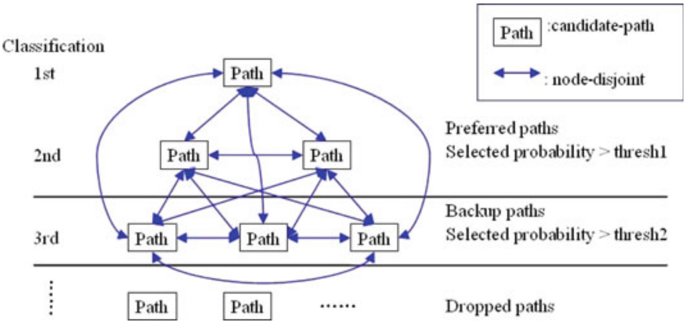


Fig. 5 The node-disjoint and classification sketch

the shared nodes is inevitable among the paths belong to different Source-Sink pairs. In order to use the shared nodes reasonably and make them provide different qualities of services for the Interests with different importance, we adopt an adaptive method to adjust the residual energy of the sensors. We introduce a parameter ω to dynamically weight their residual energy. If the intermediate node firstly receives an Interest, $\omega = 1$. When the intermediate node receives some other different Interest which is not importance, we use the process named *negative-reinforce* to dispose of the residual energy. The parameter ω now is relative to the ordinal number of the received Interest and the value of ω decreases exponentially. The negative-reinforced residual energy is defined in (11), where, E' denotes the disposed residual energy, E_c denotes the current residual energy, k denotes the ordinal number of the received Interests.

$$E' = E_c \times \omega \left(\omega = k^{-2^{(k-1)}}, 0 < \omega \leq 1\right) \tag{11}$$

If the intermediate node is not in a preferred path of one Interest and the currently received Interest is important, the system will reinforce the residual energy so as to provide more service for the importance Interest, otherwise, the process of negative-reinforce is still executed. The reinforced residual energy is defined in (12), where V denotes the value of *Importance* of the currently received Interest, L denotes the summation of the values of *Importance* of the Interests being about to be deployed in the scene.

$$E' = (1 + \omega)E_c \left(\omega = \frac{V}{L}\right) \tag{12}$$

With the scheme of adaptively adjusting the residual energy for the sensors, we can use the routing establishing method described above to establish paths for each Source-Sink pair in the scene with multiple Source-Sink pairs. If the established path including a intermediate node is selected as a preferred path for the new Interest, the backup path including the same intermediate node for previous Interest should be dropped in order to reserve sufficient energy for the new Interest, otherwise, the set of backup paths for the previous Interest should not be changed.

Because the residual energy will become larger than the current residual energy (the real value) after being reinforced, we should address the arising problem of reinforcing the residual energy. According to the method of establishing the routings and the strategy of balancing the traffic loads which will be stated below, the transmitting capacity of the established path will be larger than the real transmitting capacity, so the assigned transmission for the path is more than that the path can afford, and the path will become invalid before accomplishing the assigned transmission. We have not designed some new approaches to adjust the parameter, but employ the following method to solve this problem: if the path becomes invalid before accomplishing the assigned transmission, the Source will pick out a backup path with the largest selected probability to replace the invalid path to accomplish the rest transmission. Because the backup paths have been stored in the routing cache of the Source previously, the system dose not have to trigger a new process of routing discovery, and basically guarantee the continuity of communication.

3.2 The Weighted Traffic Scheduling Algorithm

According to the routing establishing algorithm stated above, we can get the number of preferred paths for an Interest which can be denoted as N. The Source estimates the quantity of reporting data denoted as S and uses a weighted traffic scheduling algorithm considering the transmitting capacity of the selected paths to assign the traffic load in balance. Because the relay nodes consume the same energy to forward a packet, the forwarding times of the $i-$th preferred path denoted as m_i is determined by the value of the attribute *power* in the Interest passed along the path. All the preferred path for the Interest together offer a total forwarding times which can be denoted as $\sum_{i=1}^{N} m_i$, the traffic assigned to each selected path is outlined in (13).

$$S_i = \frac{m_i}{\sum_{i=1}^{N} m_i} \times S \tag{13}$$

Generally, the probing task that the Source should execute is specific, we can set how long time would the probing task last, while how much data the Source can acquire in a unit time is determined by its characteristics. Hence, the amount of reported data can be estimated. If the estimation has deviation, such as the estimation is more than the real amount of acquired data, the real transmission that needs to be executed by the selected path is less than the assigned transmission, so the path will not become invalid after accomplishing the transmission. If the estimation is less than the real value, the selected path should undertake more transmission than the assigned and it would become invalid before accomplishing the transmission. In this case, the Source will pick out a backup path with the largest selected probability to replace the invalid path to accomplish the remainder transmission. Because the backup paths have been stored in the routing cache of the Source previously, the system dose not have to trigger a new process of routing discovery, and basically guarantee the continuity of communication. Hence, it will not cause significant impact on the overall performance.

The traffic scheduling method only considers the initial state that the preferred paths have the greatest transmitting capacity. However, in some practical applications, with the increase of the Source-Sink pairs, some intermediate nodes inevitably provide service for different Interests and the transmitting capacity of the preferred paths including these shared intermediate nodes is reduced. However, we do not design a scheme to dynamically adjust the original assigned traffic because of the reduced transmitting capacity. Upon the preferred path fails, the Source will pick out an appropriate backup path with the largest selected probability to replace the failed path and continue to accomplish the unfinished traffic. Meanwhile, the system startups a process of routing repair which will be outlined below, and then decides whether to set the repaired path be a backup path or not.

After assigning the traffic for each selected path, the Source then utilizes MSR to report the acquired data to the Sink. Since MSR also uses source routing, each data packet carries the complete path from the Source to the Sink as a sequence of IP address. In traditional multi-path routing protocols, they require more routing table space and computing overhead

```
(1) Establish paths between the Source and the Sink
{
    The Sink calculates the direction-angle and propagates the Interest;
    for each relay nodes
        Calculates the direction-angle and propagates the Interest;
}
(2) Calculate the selected probability for each path in the routing cache of the Source;
(3) Sort the selected probabilities in a descending order;
(4) Pre-process all paths in the routing cache
{
    if (Path[i].probability > thresh_1)
        Path[i] is a preferred path.
    else if (Path[i].probability > thresh_2)
        Path[i] is a backup path.
    else
        Path[i] is a dropped path.
}
(5) Do node-disjoint and Classification operations
{
    if (Path[i].probability is maximal)
        Set Path[i] as the most optimal path;   // Pick out the most optimal path;
    for other paths in routing-cache   // Pick out sub-optimal paths;
    {
        if (Path[j].probability = Path[k].probability & Path[j] and Path[k] are node-disjoint with the former optimal paths)
            if (Path[j] and Path[k] are node-disjoint with each other)
                Set Path[j] and Path [k] both as the optimal path of the current level;
            else if (Path[j].hops < Path[k].hops)
                Set Path[j] as the optimal path of the current level;
    }
}
(6) The Source estimates the total amount of the reported data;
(7) Calculate and assign the traffic over the selected paths;
(8) Use MSR to report the acquired data;
```

Fig. 6 The pseudo code of the operation process for the scene with one Source-Sink pair

to maintain alternative paths, however, the on-demand nature of MSR have meant that the intermediate node are not required to keep the routing information, the overhead of routing storage is reduced greatly and the storage resource of sensor is saved effectively. It can also eliminate the need for periodic routing information updating and neighbor detection at the intermediate nodes, so a great deal of computing resources are also saved. Using MSR in AEMRP-LB is in harmony with the objective of designing routing protocols for WSN.

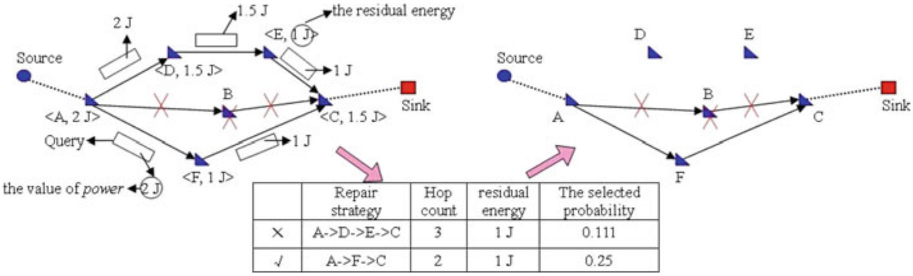
Figures 6 and 7 respectively present the pseudo code for the two aspects of AEMRP-LB: (1) the operation process for the scene with one Source-Sink pair, (2) the operation process for the scene with multiple Source-Sink pairs. The necessary explanations of some abbreviations are introduced here: Path[i] denotes the $i - th$ path; $Path[i].probability$ denotes the selected probability of the $i - th$ path; Path[i].$hops$ denotes the hop count of the $i - th$ path, Node[i] denotes the $i - th$ node, k is the ordinal number of passed Interests, Node[i]. E denotes the value of the residual energy of Node[i].

3.3 Maintain and Repair Routing

When the node with the minimal residual energy in the selected path for one Interest depletes, the path fails. However, there are still many member nodes having good transmitting capacity. In [25], the authors provided a simple framework for in time recovering the failed routing in node-disjoint multi-path routing for sensor networks with many-to-one traffic patterns, however, it should identify the sufficient conditions under which multi-paths can be recovered. In this paper, we use a method named *local-querying* to repair the failed routing by propagating Query in order to make full use of these resources. It can register the value of the residual energy of the passed node and the disposal method is the same as handling

```
(1) Establish paths for each Source-Sink pair
{
    The Sink calculates the direction-angle and propagates the $k$-th Interest;
    for each relay nodes
            if (the $k$-th passed Interest is not important)
                    negative reinforce (Node[i].$E$);
            else if (Node[i] is not in the preferred path of one Interest)
                    reinforce (Node[i].$E$);
            Calculates the direction-angle and propagates the Interest;
    if (the established path is a preferred path)
            Update the backup paths for other Interests including Node[i];
}
(2) for each Source-Sink pair
{
    Pre-process, do node-disjoint and classification operations to all candidate paths;
    The Source estimates the total amount of the reported data;
    Calculate and assign the traffic over the selected paths;
    Use MSR to report the acquired data;
}
```

Fig. 7 The pseudo code of the operation process for the scene with multiple Source-Sink pairs



	Repair strategy	Hop count	residual energy	The selected probability
×	A->D->E->C	3	1 J	0.111
√	A->F->C	2	1 J	0.25

Fig. 8 The repair process of energy-aware multi-path routing

power-value defined in Interest. The upstream neighbor of the dead node struggle a process of local querying, if the downriver neighbor of the dead node receive the Query by some intermediate nodes which are not in the preferred paths and backup paths, there will be several candidate repair strategies. The downriver neighbor will calculate the selected probability according to (10) for each candidate strategy and select an optimal routing with the larger selected probability to reply the upstream node. The selected routing also takes the trade-off between the residual energy of the intermediate nodes and the hop counts. The repaired path updates its selected probability and will be taken as a backup path. If the number of struggled nodes suppresses the number of the nodes in the original failed routing 50%, the struggling process should be stopped, since the number of hops is so large that the repaired routing is not acceptable.

We cite a case to illustrate the repair process in Fig. 8, where the intermediate nodes are labeled by their name and the value of residual energy. In the scene, if node B is depleted and the path including it fails, node A struggles a repair process of local querying. Now, there are two repair strategies: i) A->D->E->C and ii) A->F->C, We choose the strategy ii) with the larger selected probability to repair the failed path.

3.4 The Communication Delay

In AEMRP-LB, aiming at establishing multiple node-disjoint paths between the Source and the Sink, the system needs to invoke a process of path discovery which propagates the probing request named Interest in the right direction towards the Source. After all candidate paths having been established in the routing cache of the Source, the system then preprocess all candidate paths to pick out preferred and backup paths and discard those dropped paths by comparing the selected probability with the two defined thresholds. The node-disjoint and classification process is then executed in the reserved paths. The Source then prioritizes the use of these preferred paths to report the acquired data to the Sink, so the startup delay of communication is enhanced.

When one path is failed because of the energy depletion of its member node, the system will struggle a process of routing repair to attempt to build a new backup path. At the mean time, it picks out an appropriate backup path with the largest selected probability and switches the unaccomplished traffic assigned to the failed path to the selected backup path. Because the backup paths are previously established and stored in the routing cache of the Source and sorted in a descending order, it avoids the process of path discovery being invoked frequently and basically guarantees the connectivity and achieves a seamless communication. Hence, the interruption delay of communication of AEMRP-LB can be negligible.

4 Simulation Setup and Performance Analysis

4.1 Simulation Setup

In this paper, we use NS2,[1] a network simulator which is discrete event-driven and object-oriented as the simulation platform. We randomly deploy 100 sensors in the plane domain with the size of 700×500. The network topology is shown in Fig. 9, in which the Sink node whose position is fixed and far away from the probing area. We assume that the energy of the Sink and Source is not depleted during the whole simulation process, the initial energy of other sensors is set as a random value fallen in the range of [1J, 2J]. According to the settings of the wireless extend modules in NS2, we assume that the transmitter and receiver dissipate the same energy as 50nJ/bit for simplicity, so the lowest-energy-cost path in traditional schemes is just the shortest path only considering the number of hops. The energy dissipation of transmit amplifier is determined by the size of the radio coverage area. Moreover, the size of control information is 25 Bytes.

In order to investigate the impact of different performance metrics on the system lifespan, we design several distinct simulation scenarios. The characteristics of these scenarios include the following factors: i) the number of Source-Sink pairs; ii) the radius of radio coverage area; iii) the energy dissipation of the transmit amplifier (E_{tx-amp}); iv) the size of the acquired data; v) the amount of traffic (measured in the number of packets); and vi) the value of *Importance*. The five well-designed distinct scenarios shown in Table 1 respectively correspond with the five simulations stated in Sect. 4.2.

4.2 Performance Analysis

In the following, we mainly analyze the influences on the number of dead nodes in the network from the four metrics including the amount of traffic, the number of Source-Sink pairs, the radius of radio coverage area and the size of acquired data, and then evaluate the communication delay.

---

[1] NS2 Learning Guide. http://hpds.ee.ncku.edu.tw/~smallko/ns2/ns2.htm

Table 1 The characteristics of five distinct scenarios

Simulation scenarios	The number of Source-Sink pair	The radius of radio coverage area (m)	*Etx-amp* $(pJ/bit/m^2)$	The size of acquired data (Bytes)	The amount of traffic (for each Source-Sulk pair)	The value of *Importance* (random value)
Scenerio-1	1	200	100	500	1,000−17,000	[1, 5]
Scenerio-2	1–5	200	100	500	8×10^3	[1, 5]
Scenerio-3	1	100–350	50–175	500	8×10^3	[1, 5]
Scenerio-4	1–4	200	100	125–625	8×10^3	[1, 5]
Scenerio-5	2	200	100	500	8×10^3	[1, 5]

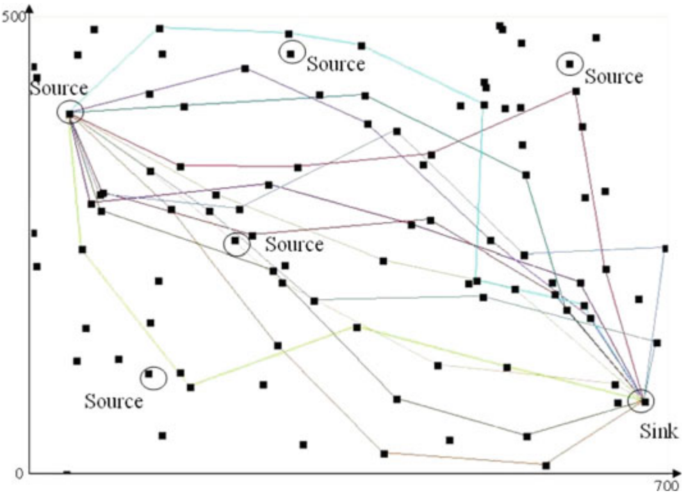


Fig. 9 The multiple node-disjoint paths

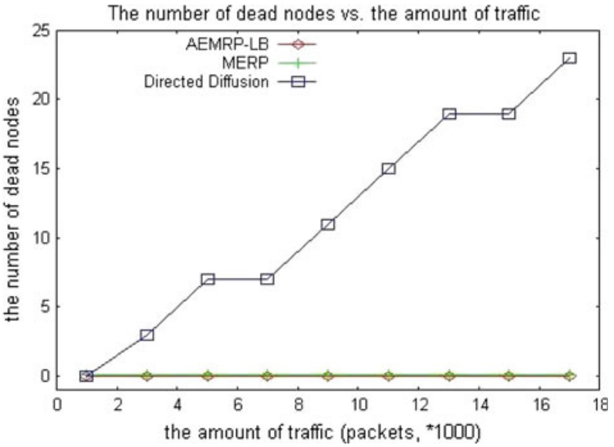


Fig. 10 The number of dead nodes vs. different amount of traffic

4.2.1 The Number of Dead Nodes vs. The Amount of Traffic

Scenario-1 shown in Table 1 is set for this section. Figure 9 depicts the multiple node-disjoint paths obtained by the method described in AEMRP-LB. We now show the impact of the amount of traffic on the number of dead nodes. The simulation result is shown in Fig. 10.

In Directed Diffusion, the Source firstly select a lowest-energy-cost path to report acquired data to the Sink until one node in the path is depleted, and then it again struggles a process of path discovery to pick out a new lowest-energy-cost path for the unaccomplished transmission. The process is executed until the transmission is completely accomplished. In MERP and AEMRP-LB, the Source selects several node-disjoint paths for the transmission. MERP assigns the reported data over the selected paths according to the probability of successful delivering a message to the Sink, while AEMRP-LB assigns the reported data over the selected paths in terms of their transmitting capacities determined by the minimal residual

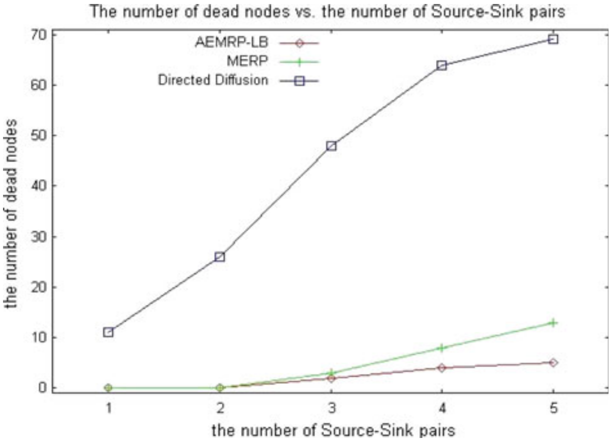


Fig. 11 The number of dead nodes vs. the number of Source-Sink pairs

energy of the nodes along the paths. When there is a certain amount of reported data, the two schemes assign the transmission over the selected paths and achieves the objective of load balance, so the number of dead nodes is reduced and the system lifespan is prolonged.

4.2.2 The Number of Dead Nodes vs. The Number of Source-Sink Pairs

Scenario-2 shown in Table 1 is set for this section, we assume that the Sources have different probing tasks and the selected paths belong to different Source-Sink pairs have few shared nodes as possible as they can. The average time interval of deploying the Interests in the scene is subjected to Poisson distribution.

With the increase of the number of Source-Sink pairs, the traffic load in the network is increased. In Directed Diffusion, more and more sensors die out owing to the depletion of energy which is caused by the heavy traffic. In AEMRP-LB and MERP, the probability of sharing nodes among the selected paths belong to different Source-Sink pairs is also increased. Although AEMRP-LB uses a method of adaptive adjusting the residual energy of these shared nodes in order to use them reasonably, there are still some shared nodes and they should provide service for different Interests inevitably and would be death quickly. While MERP does not introduce a method to dispose of the scenario with multiple Source-Sink pairs, as the increase of the number of Source-Sink pairs, the number of shared nodes depleting their energy is more than that of AEMRP-LB. The simulation result is shown in Fig. 11.

4.2.3 The Number of Dead Nodes vs. The Radius of Radio Coverage Area

Scenario-3 shown in Table 1 is set for this section. A larger radio range implies that there will be more nodes in each node's neighborhood and the network is denser. In such a scene, the number of paths from the Source to the Sink may be increased and there would be more available preferred paths. The simulation result is shown in Fig. 12.

With the increase of the radius of radio coverage area, the transmitting power is increased, so the energy dissipation of transmit amplifier is increased, in other words, the paths' transmitting capability is declined because of the total energy provided by the battery is given.

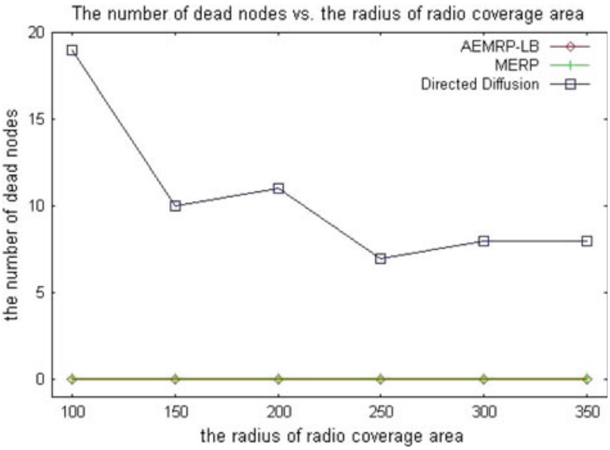


Fig. 12 The number of dead nodes vs. the radius of radio coverage area

However, on the other hand, the number of neighbors is increased for each node, there would be more paths for each Source-Sink pair. Due to the deployed amount of traffic is given in this scene, with the increase of the number of available paths, we can see that the number of dead nodes is reduced in Directed Diffusion, while, in AEMRP-LB and MERP, there would be more node-disjoint paths, they balance the traffic load more evenly and the nodes' lifespan is prolonged.

4.2.4 The Number of Dead Nodes vs. The Size of Acquired Data

Scenario-4 shown in Table 1 is set for this section. In this section, we discuss the influence of the size of acquired data on the number of dead nodes. The average time interval of deploying the Interests in the scene is subjected to Poisson distribution.

The simulation results of the three schemes are all shown in Fig. 13. According to the radio model stated in Sect. 2.1, the total communication-related energy dissipation of a node is in proportion to the size of acquired data, so the forwarding times of one node is reduced with the increase of the size of acquired data, and transmitting a given amount of reported data needs more paths. Same argument, in the scenarios with multiple Source-Sink pairs, they should use more paths and there would be more shared nodes among the selected paths. These shared nodes must provide service for different Interests inevitably and die quickly. In AEMRP-LB and MERP, owing to evenly assign the traffic load over multiple paths, the number of dead nodes is much less than that in Direct Diffusion. However, MERP did not introduce a method to dispose of the scenario with multiple Source-Sink pairs, so the node energy efficiency is worse than that in AEMRP-LB with the increase of the number of Source-Sink pair.

4.2.5 The Communication Delay

Scenario-5 shown in Table 1 is set for this section and we have taken into account the case that the nodes may become unusable caused by communication jamming and hardware failure. The communication delay consists of the communication startup delay and the communication interruption delay. The communication startup delay is defined as a time interval from system startup to the Sink receives the first data. The communication interruption delay is

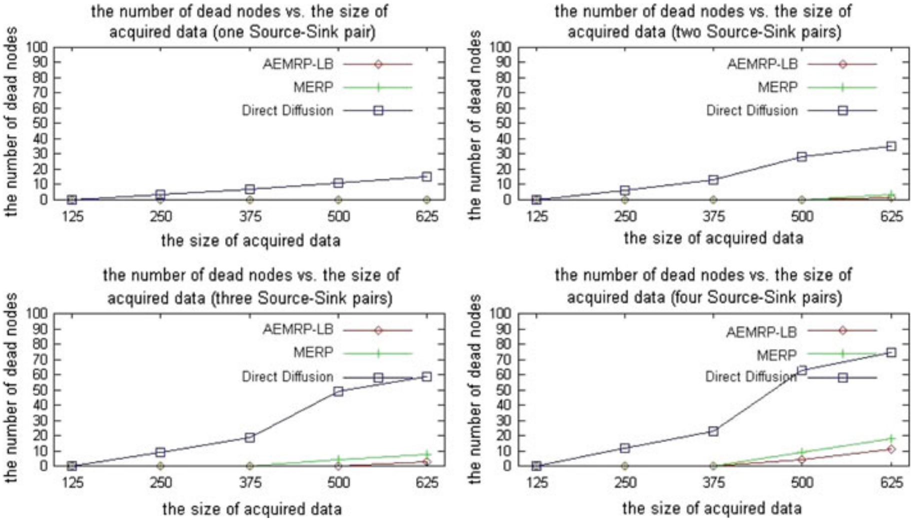


Fig. 13 The number of dead nodes vs. the size of acquired data

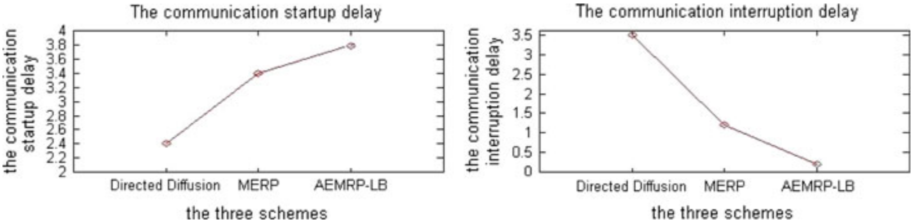


Fig. 14 The communication delay of the three schemes

defined as a time interval in which the Sink can not normally receive the consecutive reported data. The simulation results are shown in Fig. 14.

In Direct Diffusion, the system firstly establishes multiple gradient paths for the Source-Sink pair, the acquired data gathered for the Interest will be transmitted by the multiple gradient paths. Once receiving the data, the Sink will reinforce the gradient paths with the lowest energy dissipation and use the reinforced paths to transmit acquired data. In the scenario set in this paper, the lowest-energy-dissipation path is the shortest path with the least hop counts. Hence, owing to the pre-operations of gradient paths, the communication startup delay is more than that of the traditional method which only considers the number of hops. The node within the network receives an Interest from neighbors and it can not learn whether or not the Interest has been processed or the Interest is the same as the one from some neighbors in other directions. Hence, the node may receive multiple same Interest and it is beneficial to accelerate the repair of failed paths and reinforce the experienced path. The communication interruption delay is reduced compared with the traditional method, but it is still a concern that should not be ignored.

In MERP, it uses an initialization phase to exchange Hello messages and then struggles the second phase named multi-path search, so the communication startup delay is increased. In addition, it selects suitable paths in terms of their probabilities of successful delivering a message to the Sink, and balances the traffic load over the multiple paths using the probabilistic information. The transmission basically can be accomplished within the capability of the selected paths. However, the selected paths may become unusable owing to some unforeseen factors, such as communication jamming and hardware failure. In the scene with multiple Source-Sink pairs, there would be some shared nodes among the selected paths and they should provide service for the Interests simultaneously. It accelerates the death of shared nodes before they accomplishing the assigned transmission. MERP dose not introduce an effective method to address the issue and the communication interruption delay is appreciable.

In AEMRP-LB, the system needs to calculate the direction-angle to propagate the Interest, and then establishes multiple node-disjoint paths between the Sink and the Source, so the communication startup delay is much more than that of the other two schemes. AEMRP-LB also introduce a method to balance the traffic load in terms of the transmitting capability of the selected path. If one of the preferred paths fails, the system picks out an appropriate backup path and transfers the unaccomplished transmission of the failed path to the backup path. Because the backup path is established in advance and stored in the routing cache at the Source, the communication interruption delay is much less than that of the other two schemes. AEMRP-LB basically guarantees the continuity of data delivery.

5 Conclusions

The sensors with limited energy, storage and computing resources bring a great challenge for designing routing protocols in Wireless Sensor Networks and network survivability is a very important criterion for evaluating the efficiency of designed protocols. In this paper, we firstly analyze an Radio Model, and then analyze two protocols: direct communication and multi-hop routing protocol on that basis, and summarize some approaches for reducing energy dissipation.

By adopting the view that always using the paths with lowest energy dissipation to optimize energy usage at a node may not be optimal in terms of network lifespan and keeping connectivity and taking the limited resources into account, we propose an adaptive energy-aware Multi-path routing protocol with load balance (AEMRP-LB) which is on-demand, distributed and reactive. It introduces a concept named direction-angle to make the Sink and the interested intermediate nodes send Interest to those next hop nodes which are in the right direction towards the Source to avoid dissipating excessive energy caused by broadcast. And then it attempts to establish multiple node-disjoint paths by taking the tradeoff between the hop counts and the residual energy to provide a reliable data delivery. AEMRP-LB then balances the traffic over the selected paths by using a weighted traffic scheduling algorithm considering the paths' transmitting capacity and utilize the MSR to report the acquired data. MSR greatly reduces the overhead of the storage and computing resources of the intermediate nodes. In the scene with multiple Source-Sink pairs, AEMRP-LB can adaptively adjust the available residual energy of the shared nodes so as to use them reasonably and make them provide different qualities of services for the Interests with different importance.

In order to evaluate the performance of AEMRP-LB, this research undertakes a series of well-designed and detailed empirical study by adjusting the influencing factors, and the simulation results show that AEMRP-LB outperforms the Directed Diffusion and MERP schemes in many aspects, such as the energy of sensors is consumed in a more equitable way which ensures a more graceful degradation of service and the network lifespan is prolonged, the communication interpretation delay is negligible.

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References

1. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). A survy on sensor networks. *IEEE Communication Magazine* (pp. 102–114).
2. Stankovic, J. A. (2008). Wireless sensor networks. *Computer* (pp. 92–95).
3. Pan, J., Hou, Y. T., Cai, L., Shi, Y., & Shen, S. X. (2003). Topology control for wireless sensor networks. In *Proceedings of the 9th annual international conference on mobile computing and networking (MobiCom'03)*, September, 2003 (pp. 286–299). California, USA: San Diego.
4. Heinzelman, W. R., Chandrakasan, A., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Hawaii international conference on system sciences (ICSS)* 2000, (pp. 1–10).
5. Chao, H. L., & Chang, C. L. (2008). A fault-tolerant routing protocol in wireless sensor networks. *International Journal of Sensor Networks, 3*(1), 66–73.
6. Jung, S., Lee, J., & Roh, B. (2008). An optimized node-disjoint multi-path routing protocol for multimedia data transmission over wireless sensor networks. In *Proceedings of international symposium on parallel and distributed processing and applications (ISPA)*, December 2008, (pp. 958–963).
7. Shah, R. C., & Rabaey, J. M. (2002). Energy aware routing for low energy ad hoc sensor networks. In *Proceedings of IEEE wireless communications & networking conference (WCNC),* Vol. 1, March 2002, (pp. 350–355).
8. Lou, W., Liu, W., & Zhang, Y. (2006). Performance optimization using multipath routing in mobile ad hoc and wireless sensor networks. In *Combinatorial optimization in communication networks, Vol. 18*, 2006 (pp. 117–146). Springer.
9. Srinivas, A., & Modiano, E. (2003). Mininmum energy disjoint path routing in wireless ad hoc networks. In *Proceedings of the annual international conference on mobile computing and networking (MobiCom)*, 14–19 September 2003, (pp. 122–133).
10. Zhai, Y., Yang, O. W. W., Wang, W., & Shu, Y. (2005). Implementing multipath source routing in a wireless ad hoc network testbed. In *Proceedings of IEEE Pacific rim conference on communications, computers and signal processing (PACRIM)*, 2005, (pp. 292–295).
11. Nasipuri, A., & Das, S. (1999). On-demand multipath routing for mobile ad hoc networks. In *Proceedings of international conference on computer communications and networks (IC3N)*, October 1999, (pp. 64–70). MA, USA: Boston.
12. Marina, M., & Das, S. (2001). On-demand multipath distance vector routing in ad hoc networks. In *Proceedings of the ninth international conference for network protocols (ICNP)*, November 2001, (pp. 1–16). Riverside, CA, USA.
13. Yang, Y., Zhong, C., Sun, Y., & Yang, J. (2010). Network coding based reliable disjoint and braided multipath routing for sensor networks. *Journal of Network and Computer Applications, 33*, 422–432.
14. Felemban, E., Lee, C. G., & Ekici, E. (2006). MMSPEED: Multipath multi-speed protocol for QoS guarantee of reliability and timeliness in wireless sensor networks. *IEEE Transactions on Mobile Computing, 5*(6), 738–754.
15. Huang, X., & Fang, Y. (2008). Multiconstrained QoS multipath routing in wireless sensor networks. *Wireless Networks, 14*(4), 465–478.
16. Zytoune, O., El aroussi, M., & Aboutajdine, D. (2009). A uniform balancing energy routing protocol for wireless sensor networks. *Wireless Personal Communications*, doi:10.1007/s11277-009-9791-3.
17. Yin, L., Wang, C., & Øien, G. E. (2009). On the minimization of communication energy consumption of correlated sensor nodes. *Wireless Personal Communications, 50*(1), 57–67.
18. Lu, Y. M., & Wong, V. W. S. (2006). An energy-efficient multipath routing protocol for wireless sensor networks. *IEEE Vehicular Technology Conference (VTC)*, Fall, 2006 (pp. 1–5).
19. Kim, M., Jeong, E., Bang, Y. C., Hwang, S., & Kim, B. (2008). Multipath energy-aware routing protocol in wireless sensor networks. In *Proceedings of 5th international conference on networked sensing systems* (pp. 127–130).
20. Minhas, M. R., Gopalakrishnan, S., & Leung, V. (2009). An online multipath routing algorithm for maximizing lifespan in wireless sensor networks. In *Proceedings of the sixth international conference on information technology: New generations*, 2008 (pp. 581–586).

21. Xu, Y., Heidemann, J., & Estrin, D. (2001). Geography-informed energy conservation for ad-hoc routing. In *Proceedings of ACM/IEEE MobiCom'01*, July 2001, (pp. 70–84). Rome, Italy.
22. Bejerano, Y., Han, S. J., Lee, K. T., & Kumar, A. (2008). Single-path routing for life time maximization in multi-hop wireless networks. In *Proceedings of 33rd IEEE conference on local computer networks (LCN)*, (pp. 160–167).
23. Intanagonwiwat, C., Govindan, R., & Estrin, D., et al. (2003). Directed diffusion for wireless sensor networking. *IEEE/ACM Transactions on Networking, 11*(1), 2–16.
24. Wu, S., & Candan, K. S. (2007). Power-aware single- and multipath geopraphic routing in sensor networks. *Ad Hoc Networks, 5*, 974–997.
25. Cheng, W., Xing, K., Cheng, X., Lu, X., Lu, Z., & Su, J., et al. (2008). Route recovery in vertex-disjoint multipath routing for many-to-one sensor networks. In *Proceedings of MobiHoc'08*, May 2008, (pp. 209–219). Hong Kong SAR, China.

Author Biographies

Ming Tao received the B.S. degree in Anhui University, China in 2007, and the M.S. degree in South China University of Technology (SCUT), China in 2009. He is currently a Ph.D. candidate in Guangdong Key Laboratory of Computer Network in SCUT. His primary research interests include protocol design and performance analysis in the next generation wireless/mobile networks, wireless mesh and sensor technologies. Since 2007, his activities have focused on IPv6 mobility, handover management technology and routing optimization for efficient mobility support. He is an IEEE student member and has served as reviewer for several IEEE international conferences and international Journals.

Dingzhu Lu received the B.S. and M.S. degree in 2000, 2006 from Central South University (CSU), China. He is currently on the road toward Ph.D. in South China University of Technology (SCUT). He worked as a visiting researcher scholar in the Department of Computer Science, City University of Hong Kong from 2005 to 2006. His research interests include multicast and broadcast routing protocols for wireless network, mobile computing and network security. He has served as PC members for several IEEE international conferences.

Junlong Yang received the B.S. degree in Computer Science and Technology from Sun Yat-sen University, China in 2007. He is currently a postgraduate student of South China University of Technology, majors in Computer Application Technology. His primary research interests include theory and application of Multi-path routing, including protocol design and performance analysis in the multi-path routing. Since 2007, his activities have focused on multi-path routing, IPv6 mobility and Ad hoc.