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AN ENERGY-ADAPTIVE MULTIPLE PATHS ROUTING APPROACH FOR WIRELESS SENSOR NETWORKS

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A wireless sensor network (WSN) is expected to have a significant impact on military and civil applications such as target field imaging, intrusion detection, weather monitoring. Sensors are battery-powered, and hence energy-conserving communications are essential to prolong the sensor network's lifetime. Also, given the unreliable nature of the wireless channels and the high failure rate of the individual sensors, a fault tolerant routing protocol with energy-efficiency is getting more and more attention. In this paper, we propose an energy-adaptive multiple paths routing algorithm (EMRA) for wireless sensor networks. It consists of three elements: (i) gradients to disseminate data over multiple paths from a source to a sink, (ii) rules used for setting up disjoint multiple paths, and (iii) policies for selecting multiple paths. By limiting the maximum number of the gradients, the exploratory data messages forwarded is decreased efficiently. By using the rules for setting up disjoint multiple paths, the sink node can get a sufficient number of disjoint multiple paths, which enables EMRA to recover from a routing failure quickly. Our analysis and simulation results reveal that EMRA performs better than the existing multiple paths routing algorithms in terms of the average dissipated energy and the delay to set up multiple paths.

Key words: Wireless sensor networks, multiple paths, energy-adaptive
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1 Introduction

A wireless sensor network (WSN) consists of a large number of densely deployed sensor nodes with limited resources: battery, computation power, communication range, and memory size. It can be widely used in the areas of medical care, military, and disaster recovery. Routing [1] in WSNs is a challenge due to the inherent characteristics that distinguish these WSNs from other wireless networks like mobile ad hoc networks. First due to the large number of sensor nodes, it is not possible to manage a globally unique addressing scheme since the address management overhead is high. Second, sensor nodes are tightly constrained in terms of energy, processing, and storage capacities. Thus, it requires us to use resources efficiently. Third, sensor networks are application-specific (i.e., design requirements of a sensor network change with applications). For example, the challenging problem of low-latency precision tactical surveillance is different from that of a periodic weather monitoring task. Finally, data collected in WSNs is typically based on common phenomena. Therefore, there are a lot of redundancies, which need to be exploited by the data-aggregation policies to improve energy and bandwidth utilization.

Earlier works have explored the design of mechanisms for single-path routing in WSNs [4-6]. But with a single path, fault tolerance can't be provided because the continuity of end-to-end communication can't be maintained without routing protection and restoration techniques. In [3, 4], to overcome failed nodes, periodic, low-rate, network-wide flooding of events is needed to enable local re-routing. But as we know, energy efficiency is an important performance criterion. Such flooding can adversely impact the lifetime of a network. It is desirable to find alternative techniques to provide energy-adaptive and resilient routing in the presence of failure.

Motivated by reliability and energy efficiency requirements, this paper proposes an energy-adaptive multiple paths routing algorithm (EMRA) for WSNs to increase resilience to node failure. EMRA consists of three elements: (i) gradients to disseminate data over multiple paths from a source to a sink, (ii) rules used to set up disjoint multiple paths, and (iii) policies for selecting multiple paths. Gradients are set up by the interests flooding, but are different from those of directed diffusion (DD); intermediate nodes set up gradients for only a limited number of neighbours. After gradients set up, the source node will send exploratory messages to its neighbours. Intermediate node will forward this message to one of its neighbours according to its gradients and our rules. Disjoint multiple paths are set up quickly as the sink gets the exploratory messages. Then different policies are used for selecting primary path and other alternate paths. By analysis and simulation, EMRA reduces the routing overhead, delay to set up paths and average dissipated energy.

The remainder of this paper is organized as follows. A brief review of WSN routing and multipath routing is presented in section II. In section III, our energy-adaptive multiple paths routing approach is proposed. The performance evaluation is presented in section IV. In section V, our paper is concluded, and future related work is discussed.

2 Related Work

2.1 Routing Overview in WSNs

To date, a number of routing algorithms have been proposed for WSNs [1, 16-18]. How to adjust the load in the network according to the energy distribution is discussed in [16]. Some cluster based routing is used to decrease energy consumption, such as LEACH [18]. These routing mechanisms have taken into consideration the inherent features of WSNs to save energy while satisfying the application requirements. But in most of approaches [1, 3], only a single path is considered for routing, no other alternate path can be chosen as soon as the single path fails. Multiple paths routing as an effective routing scheme is getting more and more attractive. Multiple paths routing means that multiple paths between a source and a destination are established. It has been widely studied in wired and wireless networks [8, 10, and 11]. According to [10], in ad hoc networks, multiple paths routing is better suited than a single path in terms of stability and load balance. Many analyses have shown that the multiple paths routing algorithms can increase network throughput and decrease message delay. But in WSNs, energy efficiency and reliability are important for the limited energy and unstable connections. With multiple paths routing, if the working route is broken, the source node needs not waste time to find a new path for routing. It will choose another alternate path, which provides a more reliable routing, at the same time saving energy. To help you understand our algorithm better, following some related algorithms are summarized.

2.2 Directed Diffusion (DD)

Directed Diffusion (DD) proposes a new data dissemination paradigm in [4], where the sink node requests data by broadcasting interests. Fig. 1 shows the details of DD. The interest diffuses through the network hop by hop, and is broadcast by each node to its neighbours. As the interest is propagated throughout the network, gradients are set up toward the sink to draw data satisfying the query. Each sensor that receives the interest sets up a gradient toward the sensor nodes from which it receives the interest. This process continues until gradients are set up from the sources back to the sink node. After the source node receives the interest, it sends an exploratory data message to each neighbour for whom it has a gradient. After the sink node starts receiving the exploratory data, it reinforces one or multiple neighbours by sending a positive reinforcement message. Similarly, a negative reinforcement message is used to remove a redundant path. In [3], original DD is extended to a DD protocol family, which includes: (1) two-phase pull diffusion (2) push diffusion, (3) one-phase pull diffusion.

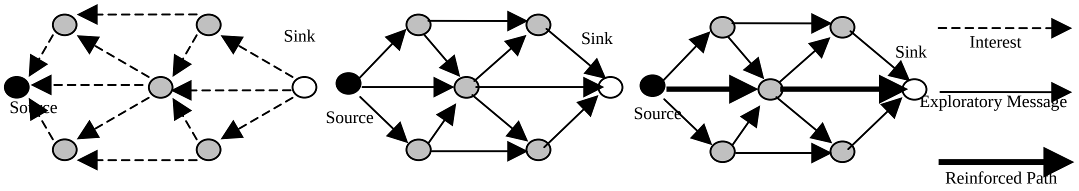


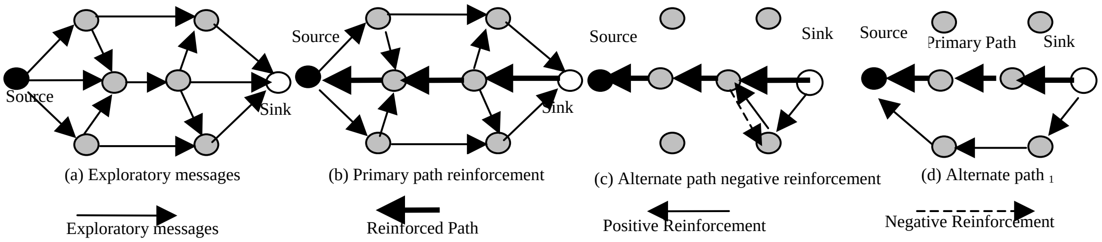
Fig. 1: An example of Directed Diffusion

In DD, multiple paths may be reinforced, but it is different from the multiple paths routing we focus on in this paper. Firstly, there are no guarantees that the multiple paths are disjoint. Secondly, when the exploratory data message is forwarded to the sink node, there are a lot of exploratory data messages in the high density network, which results in higher overhead and more energy consumption.

2.3 Disjoint Multiple Paths in Reverse Direction (DMR)

Based on Directed Diffusion, [2] proposed how to set up disjoint multiple paths and novel braided multiple paths to enable energy efficient recovery from failure of the path between a source and a sink.

DMR sets up the disjoint multiple paths by alternate path reinforcement in the reverse direction. After the source node floods the exploratory data messages (Fig. 2(a)), the sink will send its most preferred neighbour the primary path reinforcement as shown in Fig. 2(b). Next the sink node sends alternate path reinforcement to its second most preferred neighbour. And the neighbour will propagate the reinforcement to its neighbour in the direction toward the source, if its neighbour happens to be already on the primary path as shown in Fig.2 (c), its neighbour will reply with a negative reinforcement, and the node will try other neighbour. By this mechanism, a disjoint multiple paths can be constructed (Fig. 2(d)). The braided multiple paths follow the same idea but try to form a braid around the primary path. It is constructed by relaxing the requirement for node disjointedness and related braided multiple paths scheme. The alternate paths in a braid can be partially disjoint from the primary path and not completely node disjoint. Fig. 3 shows an example of a braid. As stated in [13], the braided multiple paths can easily be transformed into disjoint multiple paths, therefore in our paper; we only consider the case of disjoint multiple paths.



(a) Exploratory messages (b) Primary path reinforcement (c) Alternate path negative reinforcement (d) Alternate path 1

Fig. 2: An example of disjoint multiple paths in DMR

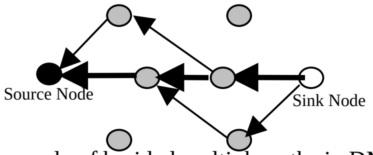


Fig. 3: An example of braided multiple paths in DMR

3 Energy-adaptive Multiple Paths Routing Approach (EMRA)

WSNs typically consist of a large number of nodes that work at a very low data rate. For the data-centric routing, a unique node identifier may not be required. Similar to DD [3], and DMR [2], EMRA is based on data-centric and uses the localized information (gradients) to find P disjoint multiple paths for different applications (Let P be the number of multiple paths required by applications). It consists of three elements: (i) gradients to disseminate data over multiple paths from source to sink, (ii) rules used for setting up disjoint multiple paths, and (iii) policies for selecting multiple paths. Following are the details about each element.

3.1 Array of Gradients

In EMRA, we find the disjoint multiple paths by the gradients in the forward direction (from a source to a sink). The array of gradients is used to control the overhead and energy consumption for exploratory data messages.

Firstly, the sink node floods the interest, which is diffused in the network. The intermediate nodes will set up an array of gradients. Here an array of gradients is not maintained for all neighbours from which the interest is received. Instead, each intermediate node will have gradients sorted by the increasing order of lowest delay for K neighbours. K is assumed to be given by applications. The number K is defined as the maximum number of gradients maintained at each node. At the intermediate nodes, m gradients are maintained, where $m \le K$. In the array, the gradients are sorted by the increasing order of lowest delay. Fig. 4 illustrates the original DD where each intermediate node keeps gradients for all its neighbours. Figures 5 and 6 illustrate the gradients when $K=2$ and $K=3$.

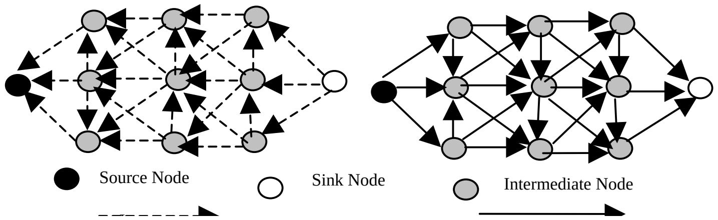


Fig.4: An example of unlimited gradients

If $K=2$, the array of gradients for each intermediate node is illustrated in Fig. 5:

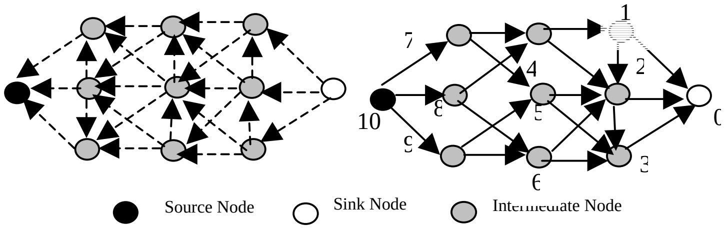


Fig. 5: An example of gradients as K=2

If $K=3$, the array of gradients for each intermediate node is illustrated in Fig. 6:

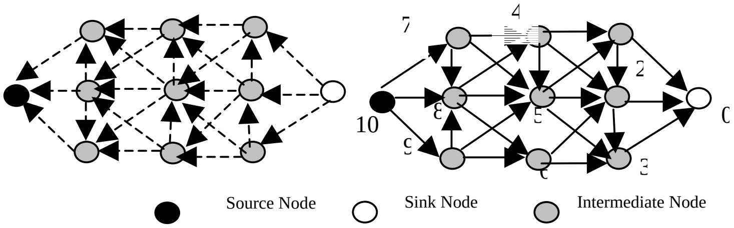


Fig. 6: An example of gradients as K=3

Table 1 shows the detailed gradients at each intermediate node when $K=3$. Here the array of gradients for each node is ordered by lowest delay.

Table 1: Gradients for each intermediate node when *K=3* (Fig. 6)

Node number	Array of gradients
Node 1	[0,2]
Node 2	[0,3]
Node 3	[0]
Node 4	[1,2,5]
Node 5	[3,2,1]
Node 6	[3,2]
Node 7	[4,5,8]
Node 8	[4,6,5]
Node 9	[6,5,8]

3.2 Rules for Setting up Multiple Paths

If the source receives the interest, it sends the exploratory data message to each neighbour. When the intermediate nodes get the exploratory data message, they will obey four rules in EMRA to forward it:

Each node will forward the exploratory data message to one of its neighbour according to its array of gradients; only one neighbour with lowest delay will be chosen first.

Each node will reject the exploratory data message if the same data message has been forwarded already.

If a neighbour with the lowest delay refuses the exploratory data message by replying with a reject message, the second neighbour in the array of gradients will be chosen, and this probing will iterate until the last neighbour.

If all neighbours in the array of gradients refuse the exploratory data message, the node will give up forwarding the data message and delete the gradients.

K is crucial for the message forwarding to the sink node. The higher *K* is, the more paths to forward the exploratory data message can be explored, and the number of multiple paths that can be established may be higher. At the same time, the more energy will be consumed. The multiple paths will be guaranteed to be disjoint by the above rules i and ii, both of which assure that the multiple paths do not share the same intermediate node. Following are the cases for *K=2* and *K=3* (refer to Fig.7 and Fig.8, respectively).

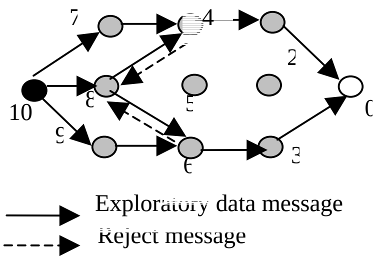


Fig.7: An example of exploratory messages as K=2

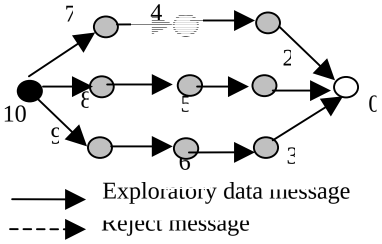


Fig. 8: An example of exploratory messages as K=3

α -Redundant EMRA (EMRA_α):

As we know, the number of multiple paths is no more than the number of source's neighbours, and in high density networks, the average number of neighbours for each node is high. To further reduce the overhead for exploratory data messages, an α -redundant (α >1) EMRA scheme can be used, where the source will send exploratory data messages to only $\alpha \times P$ neighbours. Let L be the number of the source's neighbours. In low density networks, it often happens that L<$[\alpha \times P]$; therefore in the simulations, we focus on α 's effects on high density networks. In high density networks, we can assume that P (the number of multiple paths we plan to find) <L. In α -redundant EMRA scheme, the source will not send exploratory data messages to each neighbour; instead, only $f(\alpha)$ neighbours are chosen according to their lowest delays. Where:

$$f(\alpha) = \begin{cases} L, & if\,|\alpha \times P| \geq L \\ [\alpha \times P] + 1, & if\,|\alpha \times P| < L \end{cases}$$

α can be set inversely proportional to density, and it could be also set smaller as *P* gets larger.

3.3 *Policies for Selecting Paths*

The sink node will receive M copies of the same exploratory data message from the source, which indicates there are *M* paths ($M \leq f(\alpha)$).

After M multiple paths have been found, the sink node will use two kinds of reinforcements: positive reinforcement and negative reinforcement.

Positive reinforcement: the sink node will choose only a single previous node to reinforce. Then the reinforcement message is forwarded in reverse direction hop by hop to the source node. When the source node gets the reinforcement message, it will choose this path as a primary path. If the primary path is broken, the sink node can reinforce the next path chosen from the M paths directly, and the source node will choose this alternate path as the primary path.

Negative reinforcement: *M>P*, which means there are some redundancies. To remove *M-P* paths, negative reinforcement is used. The sink node will send negative reinforcement messages to *M-P* previous hop nodes, and these neighbours will delete the gradients. This negative reinforcement will be forwarded hop by hop, and the intermediate nodes will delete their gradients.

Fig. 9 and Fig.10 show the results of positive reinforcement and negative reinforcement when *K=2* and *K=3*, respectively. In Fig. 9, *M=P=2*, positive reinforcement is implemented along two multiple paths, no negative reinforcement is implemented. In Fig. 10, *M=3*, there is a path that has been negative reinforced.

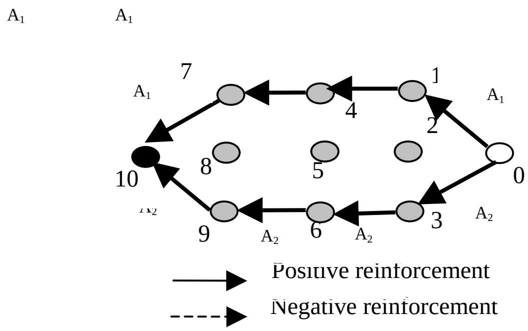


Fig. 9: The disjoint multiple paths as M=2, P=2

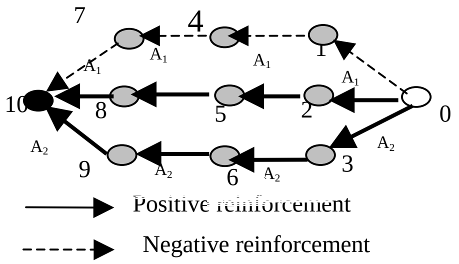


Fig. 10: The disjoint multiple paths as M=3, P=2

In this section, In EMRA, the sink gets M disjoint multiple paths as it receives the *M* copies of the exploratory data message from the source node. And the positive reinforcement can be sent directly on the multiple paths. Compared with EMRA, DMR [2] can find the primary path after the sink receives the exploratory data message. To find other alternate paths, the sink node need to try its neighbours, and the intermediate node tries their neighbours one by one (refer to Section 2), which costs more delay time to set up multiple paths, and more control traffic as well. In DD, the sink node can get the primary path as it receives the exploratory data messages, but it costs more energy than EMRA for the reason that it sets up gradients for all neighbours, and more exploratory data messages need to be forwarded, which is clear especially in the high density networks. In DD, the sink node may get a lot of exploratory data messages, which will result in a lot of negative reinforcements to be sent.

3.4 Complexity Analysis

To find the possible alternate paths, EMRA incurs little overhead: interest flooding, exploratory messages and reinforce messages. We represent the sensor network as a graph $G=(N,E)$ with a diameter d in terms of hops (i.e., the longest path between any two nodes) and the average node connecting degree is D, $K<D$. L_w represents the average length of a working path, and L_b represents the average length of a backup path $L_w \le L_b$.

DD incurs the following overhead to find a path: interest flooding + exploratory message + reinforce message= $D\times|N|+D\times|N|+L_w = 2D\times O(|N|)$ [15]. For EMRA, the overhead to get the multiple paths is: interest flooding + exploratory message + reinforce message= $D\times|N|+K\times|N|+L_w+L_b$ $=(K+D)\times O(|N|)$. For the EMRA with α - redundant scheme, the overhead is calculated as: $D\times|N|+K\times(P\times\alpha/D)\times|N|+L_w+L_b = (K\times P\times\alpha/D+D)\times O(|N|)$. In DMR, the overhead is $D\times|N|+D\times|N|+L_w+D\times|N| = 3D\times O(|N|)$. With this analysis, we can get that the overhead of DMR is maximum, and the overhead of EMRA is minimum, especially EMRA with α - redundant scheme.

4 Performance Evaluation

In this section, we use Qualnet [14] to evaluate EMRA. The distributed coordination function (DCF) of IEEE 802.11b wireless LANs is used as the MAC layer, and the radio range is set to 30 meters. In order to study the network density, networks with a varying number of nodes are analyzed. In our experiments, we use 50 to 500 static nodes to study the density effects and nodes are uniformly distributed within a 200m×200m area. And the sink node is placed at (100, 50). For each task, the source node is randomly selected. Following assumptions are similar with DD [3]: each source generates two events per second, events are modelled as 64 byte packets, interests as 32 byte packets, interests are periodically generated every 5 seconds, and the interest duration is 15 seconds. The parameters of the radio energy model are also the same as the ones in DD [3]: the idle time power dissipation is about 35mW, which is 10% of it's receive power dissipation (395mW), and about 5% of it’s transmit power dissipation (660mW).

Our evaluation consists of two parts. Firstly, three factors are tested: (i) the number of multiple paths with the value of K and the network density, (ii) the ratio of backup path’s length and primary path’s length, and (iii) the value of α in high density networks. Secondly, performance metrics such as energy efficiency and delay to set up a backup path between EMRA, EMRA_α , DD, and DMR [2] are evaluated.

To study the impact of the value of the number of gradients *K* on EMRA, we set different values of K in different network density. From the number of multiple paths M found with EMRA, we can observe the relation between *M* and *K*. In Fig. 11, in the cases of 50 and 100 nodes, there is little difference in *M* with varying *K*'s values. As the density gets higher, the difference is still very small. From these, we can conclude that the value of *K* has little effect on the number of multiple paths found by EMRA. At the same time, higher K means more exploratory data messages can be forwarded, so in our following experiments, *K* is set to 2.

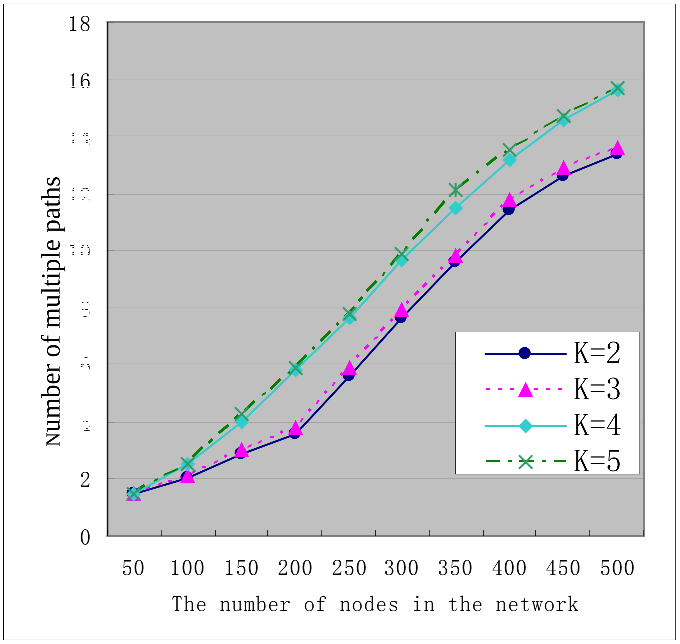


Fig.11: Number of multiple paths with different K and network density

To show the quality of the backup path in different network densities, the parameter ratio of backup path' length to primary path's length is used. In our tests, only one backup path is setup. If the ratio is high, that means the quality of the backup path is low; otherwise the quality is high. From Fig. 12, at low network densities, the backup paths are relatively longer since fewer alternate paths exist in the topologies, and a long backup path is chosen. It also shows that in high density networks, the backup path is almost as short as the lowest delay path (primary path).

The effect of α on EMRA's performance is shown in Fig. 13. In the experiments, only a high density network is tested (400 nodes, the average number of neighbours for each node is about 28), since there is little difference between EMRA and EMRA_α in low density networks (as we explained in Section 3). From Fig. 13, it is revealed that if we want to satisfy the required number of multiple paths ($M \geq P$), the α 's value is about 2.1, 1.6, and 1.36 respectively when P equals 2, 3, and 4, which shows that as *P* increases, we can choose a lower α . In EMRA without α -Redundant Scheme, the source node will send exploratory data messages to all of its neighbours. In the Fig.11, we can see that as the number of nodes in the network is set 400, the number of multiple paths found is about 11, which is consistent with the experimental result presented in Figure 13, from Fig.13, we can see that *M* is about 11 in the original EMRA.

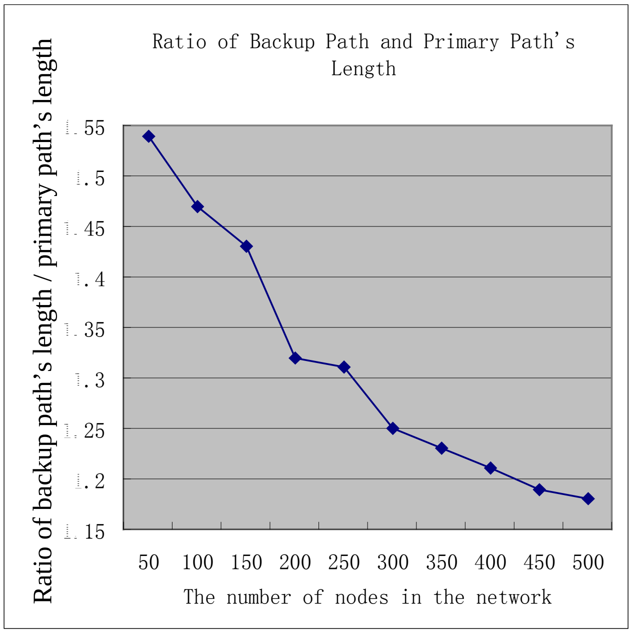


Fig.12: Ratio of backup path and primary path's length

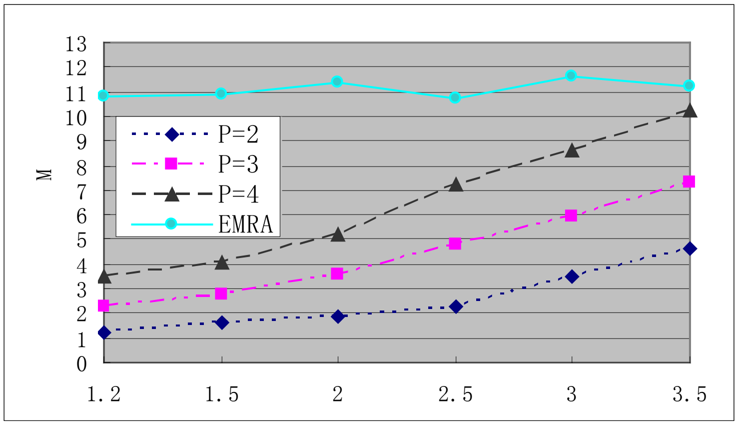


Fig.13: α 's effect in high density networks

In the second part, two metrics are chosen to compare EMRA, EMRA-α and other algorithms: average dissipated energy and delay to set up path(s).

Average dissipated energy measures the ratio of total dissipated energy per node in the network to the number of distinct events seen by the sink. This metric is used to quantify the average work done by a node in delivering each sensory data to the sink. It also hints the overall lifetime of sensor nodes.

Fig.14 shows the average dissipated energy per event as a function of the number of node in the network. Table 2 shows the parameters for each algorithm.

Table 2: Parameters for each algorithm

Algorithm	P	α
EMRA	2	
DMR	2	
EMRA-α 1	2	2.5
EMRA-α 2	3	2.0
EMRA-α 3	4	1.8

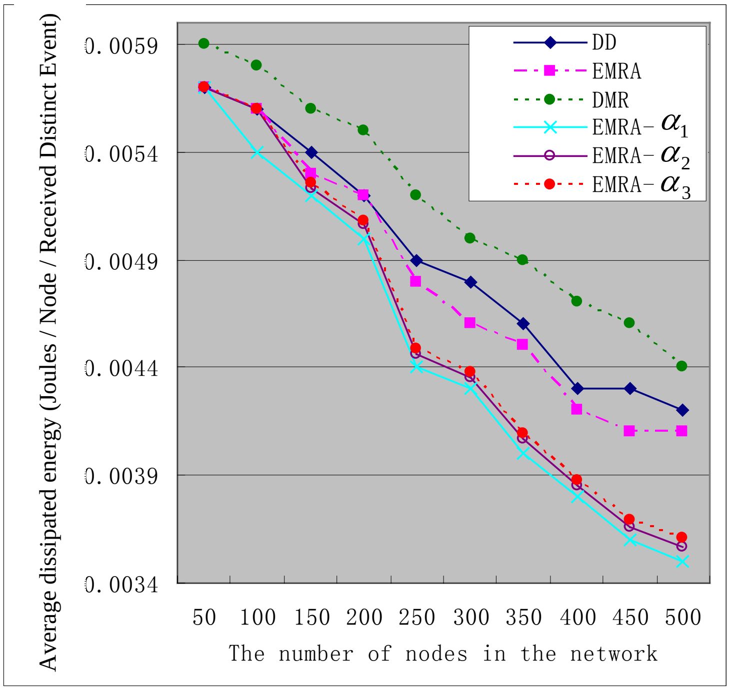


Fig.14: Average Dissipated Energy with varying network density

In the figure, the average dissipated energy per event decreases as the network density increases. DMR costs more energy than other algorithms. As the network density becomes small such as 50 and 100 nodes, the average dissipated energy per event of DD, EMRA and EMRA-α are close. However, as the network density becomes higher, EMRA, especially EMRA_α becomes more energy-efficient than DD. As the network density gets higher, more valid multiple path can be found and used in the EMRA and EMRA_alpha, which results the EMRA and EMRA_α are more energy efficient than DD. In the EMRA-α 1, EMRA-α 2 and EMRA-α 3, average dissipated energy increases as the number of P increases. From these, EMRA-α 2 and EMRA-α 3 find 3 and 4 multiple paths respectively; however, both of them cost less energy than DMR with 2 multiple paths. It shows that EMRA-α is energy-efficient.

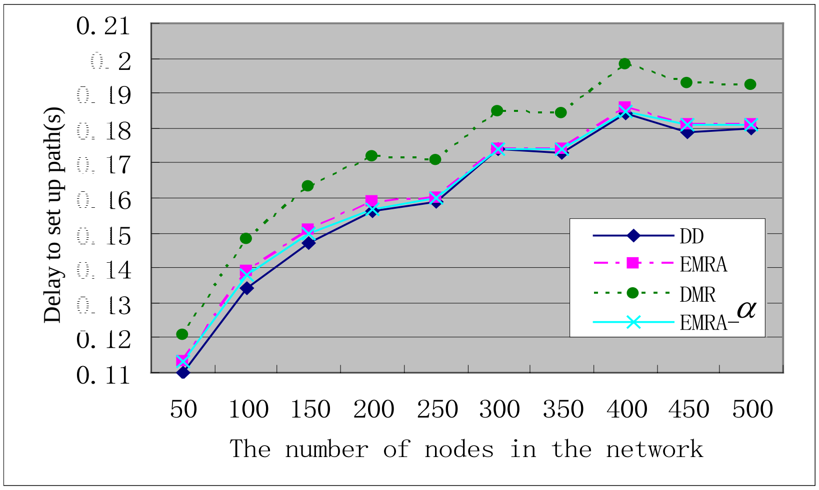


Fig.15: Delay to set up path(s)

Delay to set up path(s) is the average delay to set up path(s). The delay to set up multiple paths is an important criterion for a multiple paths routing algorithm. In our tests, only one path is reinforced in DD, and the number of multiple paths in EMRA, EMRA-α (α =2.5) and DMR is 2, which means only one backup path is set up. The delay to set up path includes three parts: time to propagate the interests, time to disseminate the exploratory data messages, and time to reinforce the path(s).

Fig.15 shows the delay to setup path(s). We can conclude that DD has the minimum delay since it just needs to find one path. DMR requires the maximum delay because it tries to find the backup path after the sink node receives the exploratory data messages, and each node tries its neighbours one by one to set up the backup paths. In Fig. 15, delays to set up multiple paths in EMRA and EMRA_α are close with the delay in DD, especially when the network density is high, which also proves that EMRA is efficient even though it sets up two paths and DD sets up only one path.

5 Conclusions and Future Work

In this paper, we propose an energy-adaptive multiple paths routing algorithm (EMRA). It consists of three elements: (i) gradients to disseminate data over multiple paths from a source to a sink; by limiting the number of gradients, overhead and energy consumption is saved evidently (ii) rules used to set up disjoint multiple paths, and (iii) policies to select multiple paths. EMRA provides an energy-efficient routing failure protection with multiple paths, which is very useful for WSNs with unstable wireless connection and limited energy. Compared with DMR that finds the multiple paths in the reinforcement phase, EMRA and EMRA_α can find disjoint multiple paths when the source initially disseminates the exploratory data messages, which reduces the delay to set up multiple paths. Compared with DD, the number of exploratory data messages is decreased significantly in EMRA, especially in EMRA_α . From the analysis and the simulation results, EMRA performs well in terms of average dissipated energy and delay to set up multiple paths.

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