

An Energy-Aware Routing Protocol for Mobile Ad Hoc Networks Based on Route Energy Comprehensive Index

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Abstract The design of energy-aware routing protocols has always been an important issue for mobile ad hoc networks (MANETs), because reducing the network energy consumption and increasing the network lifetime are the two main objectives for MANETs. Hence, this paper proposes an energy-aware routing protocol that simultaneously meets above two objectives. It first presents Route Energy Comprehensive Index (RECI) as the new routing metric, then chooses the path with both minimum hops and maximum RECI value as the route in route discovery phase, and finally takes some measures to protect the source nodes and the sink nodes from being overused when their energies are low so as to prolong the life of the corresponding data flow. Simulation results show that the proposed protocol can significantly reduce the energy consumption and extend the network lifetime while improve the average end-to-end delay compared with other protocols.

Keywords Ad hoc networks · Energy routing · Routing metric · Route discovery · Route maintenance

1 Introduction

Mobile ad hoc networks (MANETs) are self-organized dynamic multi-hop networks in which nodes are free to move and can be used as both hosts and routers [1–4]. In MANETs, nodes in most cases are powered by batteries whose capacities have not been significantly improved during recent years, which makes the limited node energy an important character for such networks. The energy depleted nodes can cause serious influence on the network. For example, if it is a source or a sink node, then the corresponding data flow will completely die; if it is an intermediate node, then it can't forward any packets which will reduce the number

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of alternative paths, even in severe cases will affect the network connectivity and integrity, resulting in network partition. To make things even worse, most traditional routing protocols only focus on its theoretical efficiency, but neglect the fact that node energy is limited. Some nodes may be overused and their energy will soon be exhausted, which not only causes packet loss and retransmissions but also wastes network resources due to route reconstructions. Therefore, routing protocols without considering node energy cannot reflect the real network performances and studying energy-aware routing has turned into an increasingly important and core issue for MANETs [5–8].

The initial motivations of our study are as follows.

- (1) When designing energy-aware routing, we should take two major aspects into consideration. One is efficiency, that is, reducing network energy consumption while ensuring network transmission quality; the other is fairness, that is, treating every node in the network in a fair manner and reducing the difference in residual energy among nodes so as to prolong network lifetime. However, most existing work pays attention to only one of the two aspects. Although some research considers efficiency and fairness, their improvements are not obvious and some important parameters are difficult to be determined.
- (2) Recent years, studying energy-aware routing policies and metrics seems to have encountered the bottlenecks, for it's hard to get rid of the shadow of the classical ones. New energy-aware routing policies and metrics for MANETs proposed in recent years are rare.

To address above problems, the protocol presented in this paper combines efficiency and fairness together. It uses Route Energy Comprehensive Index (RECI), the novel routing metric, to establish routes. It is no longer based on multi-strategy in the route discovery phase which avoids determining appropriate threshold values. Besides, it uses protection mechanism in the routing maintenance phase to protect source nodes and sink nodes from being overused so as to prolong the life of the data stream. Simulation results show that RECI can significantly reduce network energy consumption and prolong the network lifetime while reduce the average end-to-end delay.

The rest of this paper will be organized as follows. Firstly, we review the previous work on energy-aware routing for MANETs in Sect. 2 and give the energy consumption model used in this paper in Sect. 3. Then in Sect. 4, we propose the new protocol and evaluate its performance in Sect. 5. Finally we give a summary of this paper in Sect. 6.

2 Related Work

Recent years, energy-aware routing has received great attentions from researchers and its development can be generally divided into two categories.

- (1) **Dedicated to studying on routing policies and routing metrics** Typical energy-aware routing metrics have been reviewed in literature [9] and [10]. The idea of Minimum Total Transmission Power Routing (MTPR) is to select the path with minimum required transmission energy as the route, and its advantage is to maximize the energy saving. However, due to the fact that transmission energy consumption between nodes is proportional to their distance, routes established according to MTPR usually have more hops than other metrics. In addition, MTPR cannot reflect some certain nodes' residual energies. These nodes may die quickly and can have terrible influence on network performance such as the network lifetime. As a result, Minimum Battery Cost Routing (MBCR) emerges, it

chooses the path with maximum total residual energy as the route, by which way can prevent the path from being overused. However, route established based on MBCR may still contain some nodes with very little residual energy, whose exhaustions will shorten the whole network lifetime. Hence, in order not to overuse the bottleneck node (node with the minimum residual energy) so as to prolong the network lifetime, there comes Min–Max Battery Cost Routing (MMBCR), which selects the path with the maximum residual energy of the bottleneck node as the route. However, literature [11] points out that it is inappropriate to use node residual energy as the metric in some cases, and it should be replaced by node residual time, because although some nodes may have enough residual energy, their energy will drain quickly if their traffic loads are heavy. Therefore Minimum Drain Rate (MDR) has been proposed to use residual time rather than residual energy to establish routes [12].

- (2) **Dedicated to studying on energy consumption models** Recent years, studying energy-aware routing metrics seems to have encountered the bottlenecks. Therefore, some researchers start paying their attentions to energy consumption models. Based on packet retransmissions, literature [13] and [14] propose an energy consumption model that comprehensively considers each possible situation the nodes may expend energy, which makes the energy consumption more accurate. In [15], a mathematical model for energy consumption is proposed to compute the node residual energy. However, the common defect of such models is that they are complicated and some important parameters in their models cannot be accurately determined.

Among above routing metrics, MTPR only considers efficiency while MBCR, MMBCR and MDR only consider fairness. In order to take both efficiency and fairness into account, literatures [9, 11, 16] propose Conditional Min–Max Battery Cost Routing (CMMBCR), Conditional Minimum Drain Rate (CMDR) and Energy-Aware Routing Protocol (EARP) based on the idea of multi-strategy, that is, using different routing metrics to establish routes in different stages of the network. More specifically, at the beginning, more attention should be paid to efficiency, for node energy is sufficient, so MTPR is used as the routing metric to save energy. However, at later stages, node energy is no longer sufficient and the difference in residual energy among nodes is increasing, so we should pay more attention to fairness and use MDCBR or MDR as the routing metric. Although CMMBCR, CMDR and EARP can integrate efficiency and fairness to some extent, one common defect is that different network stages are divided by some certain threshold values, which are relative to the network environment and difficult to determine. Just as literatures [9] and [11] points out that the network performances will deteriorate greatly if the threshold values are inappropriate.

3 Energy Consumption Model

Research on energy-aware routing has always been based on some specific energy consumption models, and this paper is no exception. We define our model as follows. Nodes in the network mainly consist of CPU, Memory, Network Interface Card (NIC), etc. Among them, NIC's energy consumption is directly relative to the number of packets it sends and receives. So, NIC has several important parameters, namely P_{NIC}^{Tr} (the power when it is sending packets), P_{NIC}^{Rec} (the power when it is receiving packets) and P_{NIC}^{Idle} (the power when it is idle). All the values of above three parameters are fixed after the production of NIC. Due to the fact that the energy consumptions of other devices are complicated, we just assume that the sum of their power is a constant P_{other}^{sum} . Therefore, the sending power, receiving power and idle power of a certain node are as follows.

$$P_{\text{node}}^{\text{Tr}} = P_{\text{other}}^{\text{sum}} + P_{\text{NIC}}^{\text{Tr}} \tag{1}$$

$$P_{\text{node}}^{\text{Rec}} = P_{\text{other}}^{\text{sum}} + P_{\text{NIC}}^{\text{Rec}} \tag{2}$$

$$P_{\text{node}}^{\text{Idle}} = P_{\text{other}}^{\text{sum}} + P_{\text{NIC}}^{\text{Idle}} \tag{3}$$

Compared with other energy consumption models, our model is more real and easy to be implemented, suitable for researches that focus on routing policies and routing metrics. Two similar models are used in [11] and [16], however, literature [11] neglects node idle power while literature [16] brings about extra GPS energy consumption.

4 The Proposed Energy-Aware Routing Protocol

Just as Sect. 2 points out, the research of this paper belongs to the first category (i.e. dedicated to studying on routing metrics and routing policies), hence, we will respectively give the routing metric and routing policy in Sects. 4.1 and 4.2.

4.1 Routing Metric

Before giving the routing metric, we have to do some preparations such as defining the utility function of node energy consumption in Sect. 4.1.1 and defining the route energy fairness and efficiency index in Sect. 4.1.2.

4.1.1 Utility Function of Node Energy Consumption

Let RE_i^t be node i 's residual energy at time t and DR_i be the energy drain rate of node i . RE_i^t could be easily gotten online from battery management tools and DR_i is a statistical variable which is obtained from current sampling value and historical values. We use an exponentially weighted moving average method to estimate DR_i . Node i samples the instantaneous residual energy in every T s (i.e. $RE_i^0, RE_i^T, \dots, RE_i^{(n-1)T}, RE_i^{nT}$), therefore the corresponding DR_i value is

$$DR_i^n = \begin{cases} 0, & n = 0 \\ (RE_i^0 - RE_i^T) / T, & n = 1 \\ \alpha (RE_i^T - RE_i^{2T}) / T + (1 - \alpha) DR_i^{n-1}, & n = 2 \\ \beta (RE_i^{(n-1)T} - RE_i^{nT}) / T + \gamma DR_i^{n-1} + (1 - \beta - \gamma) DR_i^{n-2}, & n > 2 \end{cases} \tag{4}$$

where DR_i^n is the estimated energy drain rate in the n th period, DR_i^{n-1} and DR_i^{n-2} are the estimated energy drain rate in previous $(n - 1)$ th and $(n - 2)$ th period. α, β, γ are the coefficients that reflects the relationship among DR_i^n, DR_i^{n-1} and DR_i^{n-2} , they are all constants with a range of $[0,1]$. Owing to the dynamic topology of MANETs, we grant higher priority to DR_i s that are close to the current time of the system and set $\alpha = 0.7, \beta = 0.5, \gamma = 0.3$. Hence, the node residual time at any moment t can be expressed as:

$$RT_i(t) = \min \left(RE_i^{nT} / DR_i^n - (t - nT), 0 \right), \quad t \in [nT, (n + 1) T] \tag{5}$$

Let E_i^1 be the initial energy of node i and T_{elapse} be the duration between the time when the network starts running and the current time of system. We define the utility function of node i 's energy consumption as follows.

$$UF_i(t) = \frac{RT_i(t)}{E_i^I/P_{node}^{Idle} - T_{elapse}} \tag{6}$$

where the denominator (i.e. $E_i^I/P_{node}^{Idle} - T_{elapse}$) is node i 's maximum residual time in theory (if it doesn't send or receive any packets) while the numerator $RT_i(t)$ is its actual residual time. Because that $RT_i(t) \leq (E_i^I/P_{node}^{Idle} - T_{elapse})$, the range of the utility function is $[0, 1]$, namely $0 \leq UF(t) \leq 1$.

Actually, the utility function in this paper can be understood as the relative residual time, which can truly reflect the node's busy degree in current and future time.

4.1.2 Route Energy Comprehensive Index (RECI)

Consider path P has N nodes, we define node i 's utility coefficient as the ratio of its utility function value to the sum of all the nodes' utility function values. That is,

$$\theta_i = \frac{UF_i(t)}{\sum_{j \in P}^N UF_j(t)} \tag{7}$$

where $UF_i(t)$ can be obtained from formula 6.

From formula 7 we can see that if every node on the path has the same utility coefficient value (i.e. $0 \leq \theta_1 = \theta_2 = \dots \theta_{N-1} = \theta_N \leq 1$), then there is no difference in energy consumption among all the nodes. Therefore, inspired by information theory, we use the following method to tackle the problem of fairness. We define route energy fairness index (REFI) as

$$REFI = -\frac{\log_3^8}{N} \sum_{i=1}^N \theta_i \log_2^{\theta_i} \tag{8}$$

According to *Log sum inequality* we have

$$\begin{aligned} 0 &\leq \frac{1}{3} \log_2^3 REFI = -\frac{1}{N} \sum_{i=1}^N \theta_i \log_2 \theta_i \\ &\leq -\frac{1}{N} \log_2 \sum_N \sum_N \theta_i \leq \frac{\log_2 N}{N} \end{aligned} \tag{9}$$

Because $N \geq 2$ and REFI has the maximum value when $N = 3$, we get $0 \leq REFI \leq 1$.

It is obvious to see from formula 8 that REFI can reflect the difference in residual time among nodes on the path. The larger the value is, the less the difference is, and vice versa. Selecting the path with large REFI value can avoid network partitioning that caused by the premature deaths of the nodes. Compared with MMBCR and MDR, REFI treats all the nodes in a fair manner and thinks that all of them are equally important while MMBCR and MDR only treat the bottleneck nodes fairly. In addition, from formula 9 we can see the probability that path P contains fewer hops is high if it has larger REFI value, which means that less energy will be needed to transmit the packet from source node 1 to sink node N .

Due to the different characteristics of nodes' residual energy at different stages, we focus on different objectives when tackling the problem of efficiency. More specifically, our objective is to save the average energy consumption of the nodes when node's energy is sufficient, while the objective is to save the bottleneck node energy to prolong the network lifetime when node's energy is low. Unlike the hard-decision method used in CMMBCR, CMDR and

EARP to divide different stages mentioned in the end of Sect. 2, we propose an automatic approach that avoids the problem of determining appropriate thresholds. Specific process is as follows.

We define route energy efficiency index (REEI) as

$$REEI = \min_{m \in P} UF_m(t) \times \frac{\sum_{i=1}^N UF_i(t)}{N} + \left(1 - \min_{m \in P} UF_m(t)\right) \times \min_{m \in P} UF_m(t) \quad (10)$$

where $\min_{m \in P} UF_m(t)$ is the utility function value of the bottleneck node on path P , and it will become smaller and smaller along with the running of the network.

Formula 10 resolves the problem of efficiency by using the method of variable weight. The former part of REEI (i.e. $\min_{m \in P} UF_m(t) \times \frac{\sum_{i=1}^N UF_i(t)}{N}$) represents the average energy consumption of all the nodes on path P , and the weight is $\min_{m \in P} UF_m(t)$. The latter part of REEI [i.e. $\left(1 - \min_{m \in P} UF_m(t)\right) \times \min_{m \in P} UF_m(t)$] represents the energy consumption of the bottleneck node with the weight of $1 - \min_{m \in P} UF_m(t)$. If we regard formula 10 as a quadratic equation with one unknown parameter $\min_{m \in P} UF_m(t)$, we can derive

$$0 \leq REEI \leq \frac{\left(\frac{\sum_{j,m \in P}^{j \neq m} UF_j(t)}{N^2}\right)^2 + \frac{\sum_{j,m \in P}^{j \neq m} UF_j(t)}{N} + 1}{4\left(1 - \frac{1}{N}\right)} \quad (11)$$

Because $\frac{\left(\frac{\sum_{j,m \in P}^{j \neq m} UF_j(t)}{N^2}\right)^2 + \frac{\sum_{j,m \in P}^{j \neq m} UF_j(t)}{N} + 1}{4\left(1 - \frac{1}{N}\right)}$ is the decreasing function of N and $N \geq 2$, the range value of REEI is $0 \leq REEI \leq 1$. It's also obvious that the probability that path P contains fewer hops is high if it has larger REEI value, which is consistent with the intuitive feeling that with fewer hops the path will have a high efficiency. By integrating fairness and efficiency, we define the RECI as

$$RECI = REFI + REEI \quad (12)$$

To sum up, it is clear to see from formula 8, 10 and 12 that the definition of RECI integrates three factors: ① the difference in the residual time among nodes; ② the average residual time of the nodes on the corresponding path; ③ the residual time of the bottleneck node on corresponding path. Moreover, RECI takes efficiency and fairness together into account and avoid the difficulty of choosing proper threshold values in multi-strategy methods.

According to the energy consumption model in Sect. 3, without considering data retransmissions, the energy needed to deliver the packets from source node to sink node is less if the path has fewer hops. In addition, other network performances such as the average end-to-end delay can be improved if the path has fewer hops. However, although RECI tends to select the path with fewer hops, this is not always the case. That is, path with the maximum RECI value may not be the path with the fewest hops. Hence, the core idea of the proposed protocol in this paper is that choosing the path with the maximum RECI value from the alternative paths which have the least hop count.

Figure 1 is given to illustrate how we choose the route. Consider that there exists three alternative paths between node S and node D , and all of them contain four hops. The utility function value of each node is also shown. Intuitively, Path2 is better than Path1 and Path3. According to formula 8, the REFI values for Path1, Path2 and Path3 are respectively 0.303,

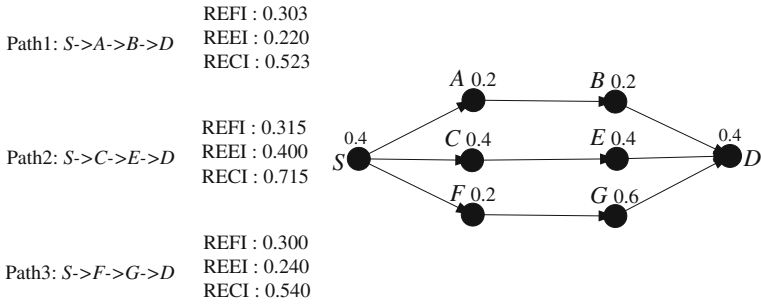


Fig. 1 Illustration for RECI

0.315 and 0.300. Similarly, using formula 10, the REEI values for Path1, Path2 and Path3 respectively are 0.22, 0.4 and 0.24.

Hence, the RECI values for Path1, Path2 and Path3 are respectively 0.523, 0.715 and 0.540. Hence, Path2 will be selected as the route.

4.2 Realization of the Proposed Routing Protocol

The routing protocol proposed in this paper is realized by extending Ad hoc On-Demand Distance Vector Routing (AODV) that uses routing metric mentioned in Sect. 4.1 instead of hop-count.

4.2.1 Route Discovery Strategy

Consider that the source node S will send packets to the sink node D . The specific working process of the proposed routing protocol is as follows:

- (a) If node D is not included in node S 's routing table or the routing expires, node S computes its energy consumption utility function value according to formula 6, fills it in the route request (RREQ) packet and finally broadcasts it;
- (b) When intermediate nodes receive the RREQ packet from node S , they should first create the reverse route to the source node, and then check whether they has recently received an RREQ packet with the same originator IP address and RREQ ID. If not, they should immediately register it and rebroadcast it after updating the energy consumption utility function value, otherwise compute the RECI value and forward the repeated RREQ packet if either of the following two conditions are satisfied.
 - ① The RREQ packet comes from a shorter (smaller number of hops) path.
 - ② The RREQ packet comes from a path with the same number of hops as the best path so far, but the RECI value is larger.
- (c) When node D receives the RREQ packet, it will not send the route reply (RREP) packet immediately but set up a timer. If it receives another RREQ packet before the timer goes off, the timer will be reset. Otherwise, it will select the best path found before the time goes off and reply the source node S with a RREP packet. Although it may increase the setup time, it can significantly save the network resources and network energy compared with the method that sending a RREP packet for each RREQ packet it receives.
- (d) When node S receives the RREP packet, the forward route has been established.

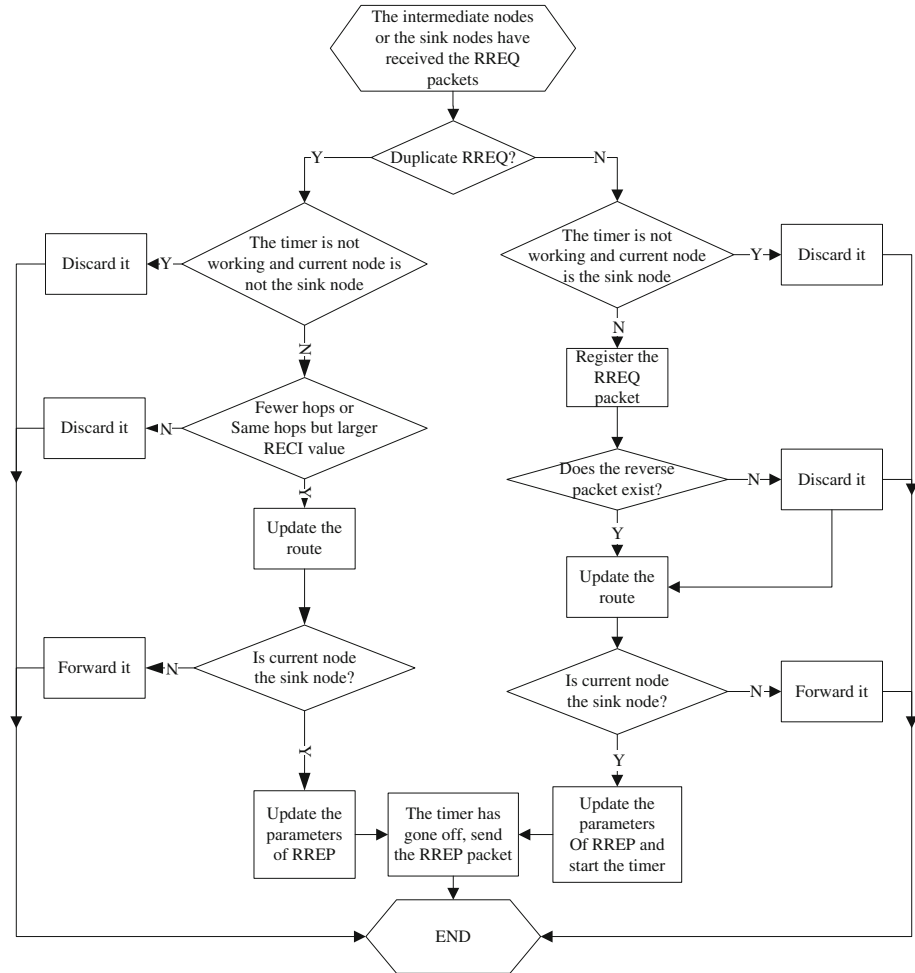


Fig. 2 Flowchart of handling the duplicate RREQ packets

In traditional AODV protocol, the intermediate nodes simply discard the duplicate RREQ packet, which can inhibit the broadcast storm. However, route discovery in energy-aware routing protocols is quite different, for the discarded packets may come from more energy-efficient paths. Hence, the intermediate nodes need to process and rebroadcast the duplicated RREQ packets if they come from a more energy-efficient path. In this paper, we present two conditions for the rebroadcast of the duplicate RREQ packets in step (b). The first condition ensures that the shortest path will be selected while the second one selects the path with maximum RECI value from all the shortest ones. The specific process for handling the duplicate RREQ packets is shown in Fig. 2.

4.2.2 Route Maintenance

Unlike non-energy-aware routing protocols, the maintenance mechanism of energy-aware routing protocols should not only consider link breakages due to the arbitrary moving of

nodes but also think whether nodes have enough energy to work normally. For source nodes and sink nodes, besides sending and receiving the packets belonging to their own data flows, they also need to forward packets belonging to other data flows, which will speed up their own energy consumption. Therefore, in order to prolong the lifetime of the data flow, the source nodes and the sink nodes must be protected when their energy is low. That is, when they predict that their residual time is below a certain level, they should broadcast route error (RERR) packets to tell their precursor nodes to reselect the next hop. It's worth mentioning that there is no protection for the intermediate nodes. The reasons are as follows. Firstly, the MANETs are characterized by multi-hop, which means that we need intermediate nodes to forward packets. Moreover, broadcasting RERR packets too often will increase network resources and the network energy consumption, which will result in reducing the network lifetime. Last but not least, the RECI metric can ensure that the difference in lifetime among nodes will not be big, which means that nodes will send the RERR packets in the same period and undoubtedly will generate the broadcast storm.

5 Simulation and Result Analysis

To evaluate the performance of the proposed protocol, the simulation scenario and environment will be designed and implemented in this section. The simulation results and analyses will also be presented.

5.1 Simulation Scenario and Parameters

The simulation is carried out on NS-2.33. The main simulation parameters are as follows. The scenario size is $1,600\text{ m} \times 1,000\text{ m}$, where nodes move according to the Random Waypoint model (RWP) with the pause time of 0 s and the max velocity of 5 m/s. IEEE MAC 802.11 is used as the MAC protocol and the channel bandwidth is 2 Mb/s. The number of nodes varies from 50 to 125. We use constant bit rate (CBR) traffic and randomly choose from 30 source–destination flows. The simulation time lasts 10 min. The detailed simulation parameters are summarized in Table 1.

5.2 Result Analysis

We compare RECI, AODV (MTPR), and CMMBCR in terms of the following performances by changing node density and data rate.

- ① Network lifetime: It is defined as the duration between the time when the network starts running and the time when half of the nodes run out of energy.
- ② Network energy drain rate: It is defined as the sum of energy consumed per second for all the nodes in the network within the network lifetime.
- ③ Average end-to-end delay: It is defined as the average delay of a CBR packet successfully delivered from the source node to the sink node within the network lifetime.

5.2.1 Varying Node Density

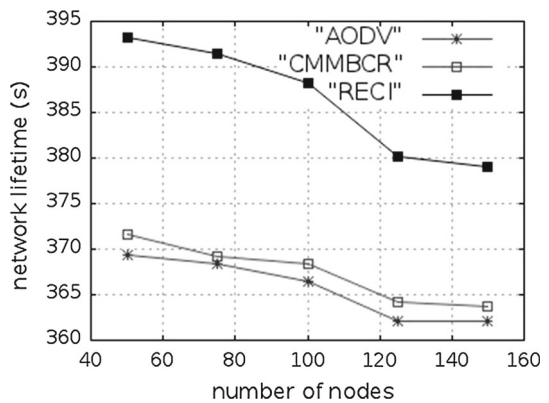
In order to evaluate the protocol with increasing node density, the data rate is set to 2 packets/s (i.e. 8 Kbps), while the other parameters are fixed, and the results are as follows.

Figure 3 shows the relationship between the network lifetime and the node density. There are more nodes participating in packet forwarding with the increase of node density, which

Table 1 Simulation parameters

Simulation platform	Software version	NS 2.33
	Scenario size/m ²	1,600×1,000
	Number of nodes	50,75,100,125,150
	Simulation time/s	600
Physical Layer	Channel propagation model	TwoRayGround
	Transmission range/m	250
	Antenna type	Omnidirectional
Link Layer	MAC protocol	IEEE 802.11 DCF
	Bandwidth /mbps	2
	Queuemode	Droptail/priqueue
Network Layer	Routing protocol	AODV/CMMBCR/RECI
Application Layer	Traffic type	CBR/UDP
	Packet size /byte	512
	Packet rate /kbps	6–15
	Number of source–sink flows	30
	Node mobility model	Mobility model
Energy consumption model [16]	Max speed /(m/s)	5
	Min speed/(m/s)	0
	Pause time/s	0
	Initial energy/J	300
	p_{node}^{Idle}/W	0.5
p_{node}^{Rec}/W	0.95	
p_{node}^{Tr}/W	1.35	

Fig. 3 Network lifetime



will make the energy drained in a more quick speed. Hence, the network lifetime of all the three routings has decreased. The network lifetime of CMMBCR is longer than that of AODV, for CMMBCR has taken the fairness of the bottleneck nodes into consideration. However, with fair treatment for all the nodes on the path as well as the protection mechanism for the source nodes and sink nodes, RECI has the longest network lifetime.

Fig. 4 Network energy drain rate

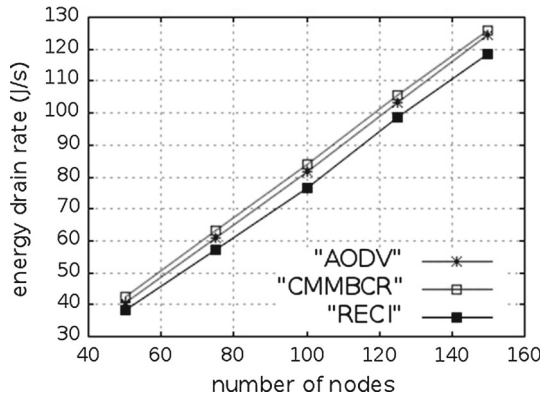
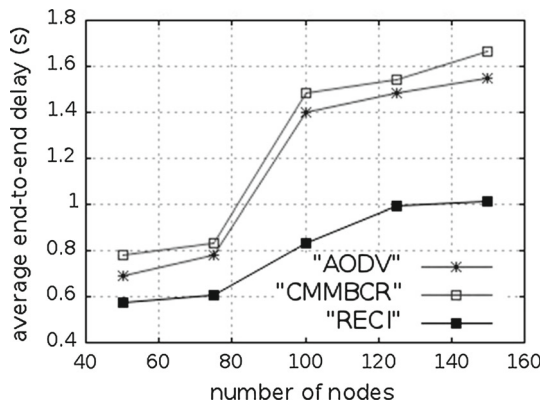


Fig. 5 Average end-to-end delay



The relationship between the network energy drain rate and the node density is shown in Fig. 4. Just for the same reason above, the network energy drain rate of all the three routings approximately increases linearly. Due the fact that the paths selected by RECI and AODV have the fewest hops, their network energy drain rates are smaller than CMMBCR's (each additional hop will consume some extra energy). Moreover, RECI has considered the energy efficiency of the route based on least hop count, which ensures that the paths are more energy saving than those of AODV.

Figure 5 shows the relationship between the average end-to-end delay and the node density. The interference increases sharply when the node density grows large. Hence, along with the increase of node density, the delay of all the three routings rises. The delay of AODV is slightly shorter than that of CMMBCR, for AODV establishes the routes based on the least hop count and each additional hop will increase packet latency. However, the proposed routing chooses the path with the maximum RECI value from the alternative paths with the least hop count, so its delay is superior to that of the other two. And the number of the alternative paths increases when the node density grows, which will make the superiority more obvious.

Fig. 6 Network lifetime

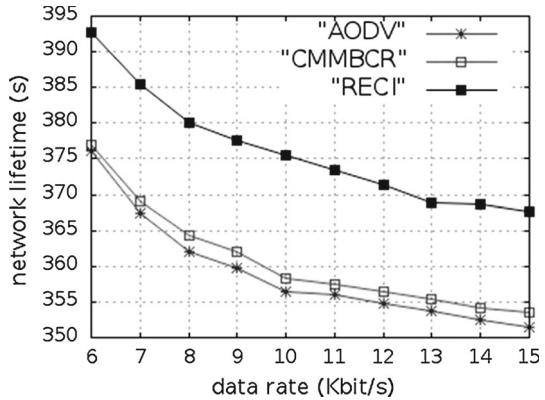
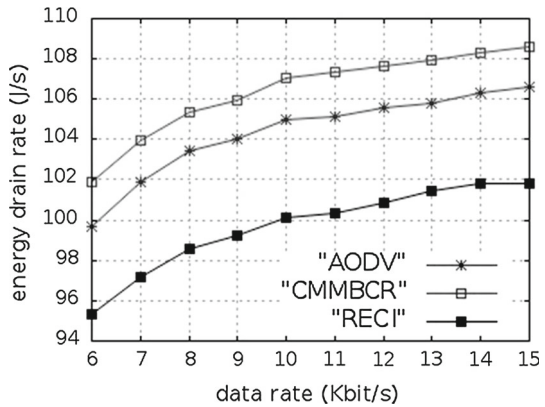


Fig. 7 Network energy drain rate



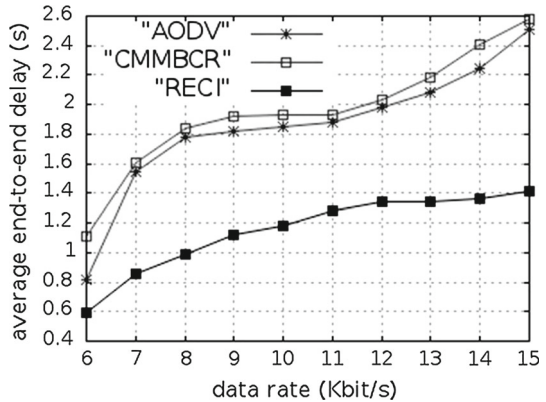
5.2.2 Varying Data Rate

In order to evaluate the protocol with different data rates, the number of the nodes is set to 125 while the other parameters are fixed. The results are as follows.

The relationship between the network lifetime and data rate is shown in Fig. 6. Nodes consume energy more frequently with the increase of data rate, therefore the network lifetime of all the three routings decreases. CMMBCR's network lifetime is longer than AODV's, for it takes the residual time of the bottleneck nodes into consideration. However, for RECI, the fairness aspect makes the difference in residual time among nodes smaller while the efficiency aspect can ensure avoiding choosing nodes with heavy traffic load.

The relationship between the network energy drain rate and data rate is shown in Fig. 7. Just for the same reason above, the network energy drain rate of all the three routings increases. Because that the paths selected by CMMBCR have the most hops, its network energy drain rate is smaller than that of AODV and RECI. Furthermore, the paths established by RECI not only have the least hop count but also are more energy efficient, which ensures that the paths are more energy saving than those of AODV.

Figure 8 shows the relationship between the average end-to-end delay and the data rate. The interference caused by channel contention and packet collision increases sharply when the data rate grows higher. Hence, the delay of all the three routings rises with the increase of data rate. The delay of CMMBCR is longer than that of AODV, for routes built by CMMBCR

Fig. 8 Average end-to-end delay

usually have more hops than those of AODV. Moreover, RECI combines energy efficiency and least hop count, which makes the delay more superior to that of the other two.

From above simulations, we can reach the conclusion that compared with AODV and CMMBCR, routes established by the proposed protocol are more energy efficient and fairer.

6 Conclusion

Fairness and efficiency have been the two major issues in the design of energy-aware routings. Where, fairness determines the network lifetime while efficiency determines the network energy drain rate. Although energy-aware routing protocols based on multi-strategy can be both fair and efficient to some extent, the appropriate choosing of threshold has been a major problem of this method. By defining the route energy comprehensive index (i.e. RECI) and taking low-energy protection measures for source nodes and sink nodes, this paper presents a new energy-aware routing protocol to successfully solve the two problems in designing energy-aware routings (i.e. prolonging network lifetime and reducing network energy consumption).

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