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An Energy-Aware Geographic Routing Protocol for Mobile Ad Hoc Networks

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Abstract Mobile ad hoc networks (MANET) are characterized by multi-hop wireless links and resource constrained nodes. To improve network lifetime, energy balance is an important concern in such networks. Geographic routing has been widely regarded as efficient and scalable. However, it cannot guarantee packet delivery in some cases, such as faulty location services. Moreover, greedy forwarding always takes the shortest local path so that it has a tendency of depleting the energy of nodes on the shortest path. The matter gets even worse when the nodes on the boundaries of routing holes suffer from excessive energy consumption, since geographic routing tends to deliver data packets along the boundaries by perimeter routing. In this paper, we present an Energy-Aware Geographic Routing (EGR) protocol for MANET that combines local position information and residual energy levels to make routing decisions. In addition, we use the prediction of the range of a destination's movement to improve the delivery ratio. The simulation shows that EGR exhibits a noticeably longer network lifetime and a higher delivery rate than some non-energy-aware geographic routing algorithms, such as GPSR, while not compromising too much on end-to-end delivery delay.
Key words: constrained flooding; energy-aware routing; MANET

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1 Introduction

Topology-Based routing protocols become not suitable for MANETs when the nodes are highly mobile because of the excessive overhead of maintaining up-to-date network topology information. In recent years, geographic routing algorithms have been extensively studied due to the popularity and availability of positioning services such as the global positioning system (GPS). Geographic routing is a promising candidate for large-scale wireless ad hoc networks due to its simplicity and scalability. Since geographic routing does not require a route management process, it carries a low overhead compared to other routing schemes, such as proactive, reactive, and hybrid topology based routing protocols.

The most significant difference between MANETs and traditional networks is the energy constraint. Some applications such as environment monitoring need MANETs

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to run for a long time. Therefore, extending the lifetime of MANETs is important for every MANET routing protocol. Imbalanced loads will deplete the energy of some nodes very quickly resulting in a short lifetime for MANETs. However, most geographic routing algorithms take the shortest local path, depleting the energy of nodes on that path easily.

In addition a hole diffusion problem may arise due to energy exhaustion of the hole boundary nodes. The nodes located on the boundaries of holes may suffer from excessive energy consumption since the geographic routing tends to deliver data packets along the hole boundaries by perimeter routing if it needs to bypass the hole. This perimeter routing scheme results in the nodes on the boundaries of holes being more likely to be used for data delivery than other nodes. This can enlarge the hole because of the excessive energy consumption of the hole boundary nodes. We call this a hole diffusion problem. Furthermore, congestion may occur in the hole boundary nodes if multiple communication sessions are bypassing a hole simultaneously. The bigger the hole is, the more serious the problem becomes.

Many geographic routing protocols assume that the geographic information is accurately available. In fact, all location services update their geographic information periodically. Typically, there can be a time difference between the update of and the demand for this information, which introduces inaccuracy in the geographic information. A short update cycle will result in large network loads and energy consumption. Moreover, since there is no perfect location service, it is possible that information transmitted to the location servers may get lost. This will aggravate the inaccuracy of geographic information. Last but not least, the accuracy of GPS is limited. Consequently, we should define the packet destination as an area rather than a point.

Given the stringent energy constraints in MANET and the inaccurate location information resulting from the factors discussed above, in this paper we present Energy-Aware Geographic Routing (EGR), a novel geographic routing algorithm combining local position information and balancing node energy consumption. It forecasts the destination node's movement to ensure packet delivery and to prolong the network lifetime. We propose a right-hand rule based on energy balance to handle the energy problem brought about exclusively by perimeter routing. In the simulation, the EGR exhibits noticeably longer network lifetime than non-energy-aware geographic routing algorithms, but does not compromise the end-to-end delay and the delivery ratio.

The rest of the paper is organized as follows. We briefly introduce some related work in Section 2. In Section 3, we explain the exchange of information between nodes and the detail of the EGR algorithm. Section 4 presents the simulation of several protocols for comparison purposes and analyze the efficacy of the EGR algorithm. We also suggest future research topics in the conclusion.

2 Related Work

Early research of geographic routing includes DREAM[1] and LAR[2] that proposed constrained flooding. The *expected zone* is defined by predicting the boundary of the destination node's movement. In both protocols, prediction is made based on on the time difference between sending data and the location information's update, as well as the destination node's speed. We adopt this approach in our routing protocol and describe it in the third section. In the LAR protocol, before the transmission of a data packet, the source node finds a route by flooding routing packets in its *request zone*. In the DREAM protocol, however, according to the location information, the data packet is flooded in a restricted directional range without sending a routing packet. Although this kind of forwarding effectively guarantees delivery, its energy use is notably high, especially in large-scale networks.

Recently, *Local maxima* in geographic routing have received much attention. Many routing protocols for planar network graphs are presented for solving this problem, such as GFG[3], GPSR[4], GOAFR+[5] and CLDP[6].

In the following, we review the shared characteristics of these geographic routing algorithms. Geographic routing schemes use greedy routing where possible. In greedy routing, packets are stamped with the position of their destination; and a node forwards a packet to a neighbor that is geographically closer to the destination. Local maximum may exist where no neighbor is closer to the destination. In such cases, greedy forwarding fails, and making progress toward the destination requires another strategy. In particular, the packet needs only to find its way to a node closer to the destination than the local maximum; at that point, greedy routing may once again make progress.

In planar network graphs, geographic routing schemes recover similarly by face routing. Note that a planar graph consists of faces and enclosed polygon regions bounded by edges. Geographic routing uses a primitive to traverse planar graphs: the right-hand rule. The right-hand rule, which the GFG and GPSR use, tours a face in a cycle, and thus can walk a face.

Note that if the graph is not planar, face routing may fail. Wireless networks' connectivity graphs typically contain many crossing edges. A method for obtaining a planar subgraph of a wireless network graph is thus needed. Greedy routing operates on the full network graph, but to work correctly, face routing must operate on a planar subgraph of the full network graph. Geographic routing algorithms planarize graphs using two planar graph constructs that meet that requirement: the Relative Neighborhood Graph (RNG) and the Gabriel Graph (GG). The RNG and GG give rules for how to connect vertices placed in a plane with edges based purely on the positions of each vertex's single-hop neighbors. Up to the present, literature, such as GOAFR+, CLDP and LCR[18], has focused on methods of deleting these crossing links.

Furthermore, based on the above research, the hop count may reduce by subtly removing some edges around the hole. Recently, Ma et al.,[20] presented a strategy, called a PP (path pruning) algorithm, to reduce the excessive number of hops caused by the detouring mode of geographical routing protocols. It finds routing shortcuts by exploiting the channel listening capability of wireless nodes and is able to reduce a number of hops with the help of state information passively maintained by a subset of nodes on the route.

However, there are several drawbacks to pure geographic routing. In certain circumstances, one cannot guarantee delivery by greedy routing, for example, when there is the rapid movement of nodes. Because of this, the location information of a destination node is rather inaccurate. Secondly, greedy routing is a single-path transmission process which means once the process drops a data packet the whole routing fails. Thirdly, there have been several schemes to overcome the *Local maxima*.

All the schemes can be classified into two categories: perimeter routing[5,6] and the back pressure rule[7,8]. In perimeter routing the system tends to route data packets along the boundaries of holes, but the perimeter routing cannot avoid the excessive energy consumption and data congestion in these nodes. Using the back pressure rule, the system returns the data packets to the upstream node in an attempt to find another route to the destination. This rule may generate an additional routing overhead.

As stated in the introduction, we should take energy into account, as it is an important element in the design of routing protocols. So far, related protocols designed for a static wireless sensor network are GEAR[11], PAMAS[12] and GREES[13]. However, most of these protocols do not perform well when the network's topology changes quickly. In GEAR, it takes a while for a node to learn about the surrounding situation. So the "learning ability" that GEAR grants to a node makes forwarding more effective and energy-balanced, but in a mobile network, there is no time to obtain up-to-date knowledge of rapidly changing surroundings. Similarly, in GREES, as an important part of the local weighting for choosing a forwarding neighbor, the system accurately calculates the FDR (Frame Delivery Ratio) by a series of HELLO messages, which can take a considerable amount of time. Consequently, GREES is suitable for a network whose topology alters slowly or hardly at all.

Mobile networks use a power-aware routing protocol in Ref.[17]. However, to save energy as much as possible, its iterative relay process will result in unacceptable end-to-end delay. Due to the non-linear attenuation of wireless signals, it is possible that one hop consumes more energy than multiple hops. Yet it can be impractical to change from one hop to several, following the mechanism of Ref.[17]. The end-to-end delay may increase signficantly, especially in a high-density network.

3 EGR Routing Protocol

3.1 Dissemination of location and energy information

When considering an ad hoc network with n nodes, we assume the existence of a mechanism that allows each node to be aware of its own location and residual energy. These coordinates and energy values are exchanged among nodes so that each node obtains the information about the other nodes in the network for routing purposes. To reduce network overhead, each node broadcasts a message about its *ID* and location to any other nodes periodically over a long period, T. On the other hand, every node broadcasts a HELLO message (beacon) regarding its *ID*, location and residual energy value to its neighbor nodes periodically over a short period, t. In our protocol, only the neighbors gain residual energy information about each other. Furthermore, according to Basagni et al.,[1], the longer the distance between two nodes, the lower the update frequency of information can be. This is consistent with our simulation. Each node maintains a Location and Energy Table (**LET**), which includes the above information and its time of update.

There is no need for each node in the EGR to be aware of all of the other nodes' information, and we can adopt any existing Location Service (LS) schemes such as[14−16] in the simulation. Nevertheless, we use flooding in the DREAM protocol[1] in our simulation uniformly for convenience, as LS is not a main concern in our paper and it just works as a tool. Although there is quite a high cost to the flooding of information compared with the LS, it will not have a negative influence on the comparison in our simulation, because all of these routing protocols uniformly employ this method to help nodes acquire correlated information. Consequently, the resource consumption is similar for all these protocols.

3.2 Forwarding data packet

The following describes the model for our protocol. We update the latest location information of D to its location server att_0. At t_1 ($t_1 - t_0$¡ T) a source node S wants to transmit a data packet P to$D$, and it acquires the location of D from D's location server (in our simulation, S gets the location from its own **LET**). Then S adds the location of D and itself as well as time difference $t_1 - t_0$ to P's header.

As is shown in Fig.1 (a), we adopt the scheme of Ref.[1] for predicting the destination node's expected zone. The center of the zone is the coordinate of D at t_0, and the radius of the zone is the upper boundary of the predicted distance of D's movement. The destination of a data packet should be an area. However, we attempt to make some optimization. From Fig.1, we see that the restricted region for the relay is in the grey areas of the three models. We employ flooding in the area of the EGR, whose borderline is defined by a red circle in Fig.1. Therefore, EGR markedly reduces the cost of flooding, compared with the LAR and DREAM. In the DREAM, if S is quite far away from D, the angle θ will be too small for S to find the next hop. Consequently, we modify the former tangents to the outer tangent lines between the two circles. One circle is centered on S whose radius is the transmission distance of S. The other is the scope of D's expected zone.

As described above, flooding in the EGR is constrained in the range of the flooding area, while we relay the data packet, in terms of the mechanism for selecting the next hop, along a single path in the forwarding area.

The coordinates of S is defined as $(x_S\,, y_S)$ and D's location is $(x_D\,, y_D)$. The maximum speed of D is v, and the radius of the flooding area is $r_D = v(t_1 - t_0)$. If v is not known and only its probability density function $f(v)$ is available, we can get r_D for a given probability p from the following expression:

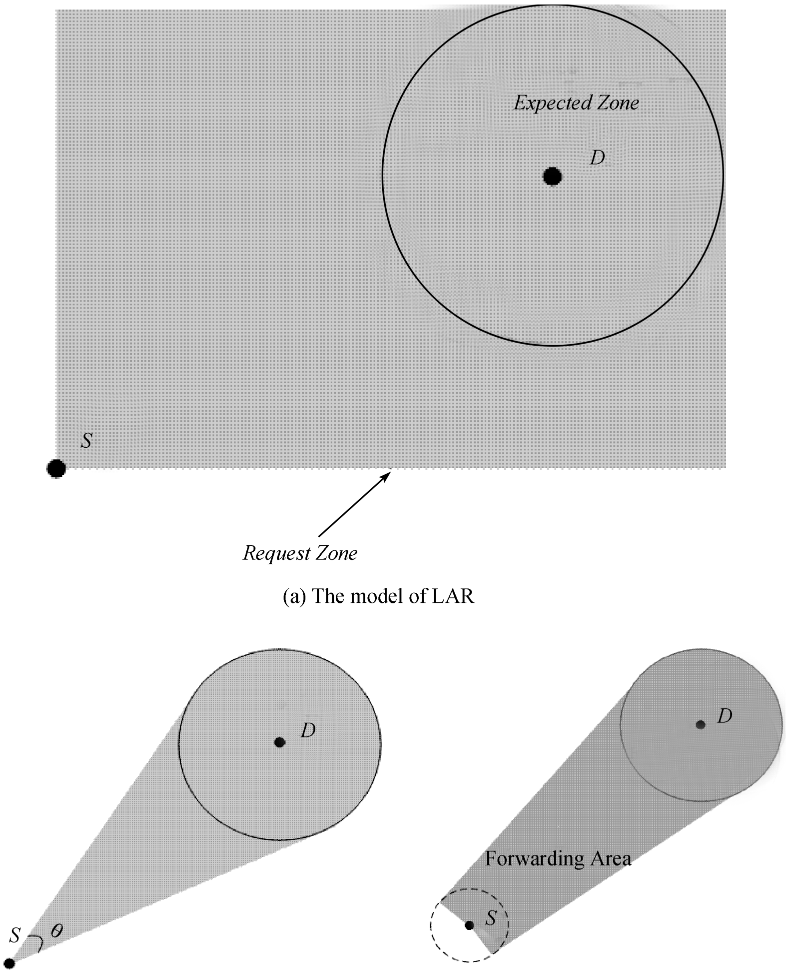
$$P(r_D \leqslant v(t_1 - t_0)) = P(v \geqslant \frac{r_D}{t_1 - t_0}) = \int_{\frac{r_D}{t_1 - t_0}}^{\infty} f(v)dv = p \tag{1}$$

To attain the two tangent borderlines, their equations are denoted as $ax+by+c = 0$. From the following equations:

$$\{ \begin{matrix} \frac{|a\,x_S + b\,y_S + c|}{\sqrt{a^2+b^2}} = r_S \\ \frac{|a\,x_D + b\,y_D + c|}{\sqrt{a^2+b^2}} = r_D \end{matrix} , \tag{2}$$

we can obtain the equations of the two lines:

$$\begin{aligned} &(x_1\,y_1 \pm r\sqrt{x_1^2 + y_1^2 - r^2})x- \\ &(x_1^2 - r^2)y - x_S(x_1 y_1 \pm r\sqrt{{x_1}^2 + {y_1}^2 - r^2}) + y_S({x_1}^2 - r^2) \\ &+\alpha r_S\sqrt{(x_1 y_1 \pm r\sqrt{{x_1}^2 + {y_1}^2 - r^2})^2 + ({x_1}^2 - r^2)^2} = 0 \end{aligned} \tag{3}$$



(a) The model of LAR

(b) The model of DREAM (c) The model of EGR

Figure 1. The models of three location-based routing.

where $x_1 = x_D - x_S$, $y_1 = y_D - y_S$ and $\alpha = \begin{cases} 1, & if \quad {x_1}^2 - r^2 \geqslant 0 \\ -1, & if \quad {x_1}^2 - r^2 < 0 \end{cases}$, $r = |r_S - r_D|$, and r_S is the transmission distance of S.

3.3 Basic mode

First, we define the following:

The distance between nodes i and j is denoted by $d(i, j)$; N_i is the set of node i's neighbors; e^j_{remain} represents node j's remaining energy shown in the **LET** of i; and F is the set of all nodes in the forwarding area of S.

When S wants to send a data packet P to D, S acquires the location of D from its **LET** or LS. Then S assembles P with the *ID*s and coordinates of S and D, the packet sequence number, the time difference and next hop's *ID* (*NEXTHOP*). After that, P is relayed to the next-hop node.

The rule of forwarding is as follows. If node i receives P, it examiens P's header to confirm the forwarding area and flooding area. Then i will take the following measures according to different situations:

If node i is located in the forwarding area (as shown in Fig.1(a)): i chooses the next hop from its neighbor nodes given by

$$\tilde{N}_i = \{j : d(j, D) < d(i, D), j \in N_i \bigcap F\} \tag{4}$$

$$NEXTHOP = k : e^k_{remain} = \max\{e^j_{remain}\}, j \in \tilde{N}_i$$

which means i chooses the next hop k with the most residual energy from all its neighbor nodes whose positions are closer to D than i.

If node i is located in the flooding area: *i relays* P to its neighbors which are in the flooding area.

During the course of forwarding, if the transmission ranges of any intermediate node i cover sthe whole flooding area, all the nodes that hear the message will not forward P, as the destination node has already received the packet. Thus, we can reduce network resource use. This is particularly true when the flooding area is not larger than the transmission range, and hardly any flooding exists during the relaying of the data packet.

3.4 The right-hand rule based on energy balance

To overcome the *Local maxima*, the GPSR employs a mechanism called the right-hand rule. First, we discuss key aspects of the GPSR and then how this relates to our new measure.

We know the goal of greedy forwarding is to gain the maximum distance in every hop. Similarly, the intention of the right-hand rule or perimeter routing is to make the best progress so that the packet can traverse the node hole. Figure 2 provides an example of a node hole, which demonstrates the right-hand rule in the GPSR. Nodes X, A_1, A_2, A_3 and D, are the boundary nodes of the hole. A packet P destined for D, is forwarded at X and encounters a *Local maxima.* We define the angle between $\overline{XD}$ and $\overline{XA_i}$ as $\theta_i(\theta_i < \pi)$, and then attain $\Delta\theta_{i,i+1} = \theta_i - \theta_{i+1}$. What the right-hand rule attempts to do is to maximize the angle progress $\Delta\theta$ in each process of choosing the next hop. For instance, when P arrives A_1, the node examines P's header and learns the last-hop link $\overline{XA_1}$' angle θ_1. After that, A_1 selects the next-hop node in its neighbor set, which can maximize $\Delta\theta$. Because of this, P is relayed to A_2. In addition, while X chooses its next hop, its last-hop link's angle θ_0 is set as π.

From Fig.2, we can see that forwarding P along the boundary of the convex polygon ($X \to A_1 \to B_1 \to C_1 \to D$) allows angle progress $\Delta\theta$ in each hop to be positive. Figure 3 shows another case in which the polygon is concave. Among the $\Delta\theta_{i,i+1}$ ($i = 1, 2, 3, 4$), only $\Delta\theta_{1,2}$ is negative, while the total angle progress is positive during the procedure $X \to A_1 \to A_2 \to A_3 \to A_4 \to D$.

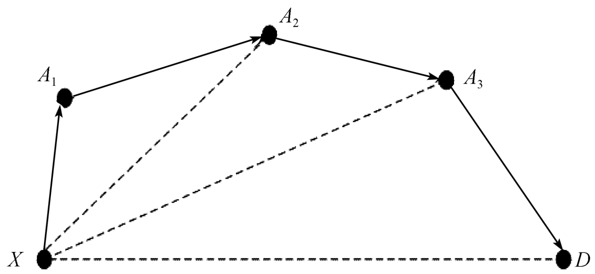


Figure 2. The case of convex polygon in perimeter routing

Having analyzed both situations above, we are able to formulate our version of the right-hand rule. When P arrives at a node i by perimeter routing, i determines the next-hop node by:

$$NEXTHOP=\begin{cases} k:\Delta\theta_{i,k}=\min\{|\Delta\theta_{i,j}|\}, j\in N_i & if\{j:\Delta\theta_{i,j}>0, j\in N_i\}=\phi \\ k:\Delta\theta_{i,k}=\max\{\Delta\theta_{i,j}\}, j\in N_i & otherwise \end{cases} \tag{5}$$

Nevertheless, according to the pure right-hand rule, the boundary nodes of the hole suffer from higher energy consumption, compared with other nodes in the network. Eq.(5) leads us to introduce our new right-hand rule based on energy balance:

$$NEXTHOP=\begin{cases} k:e^k_{remain}=\max\{e^j_{remain}\}, j\in N_i \; if\{j:\Delta\theta_{i,j}>0, j\in N_i\}=\phi \\ k:e^k_{remain}=\max\{e^j_{remain}\}, j\in\{j:\Delta\theta_{i,j}>0, j\in N_i\} \; otherwise \end{cases} \tag{6}$$

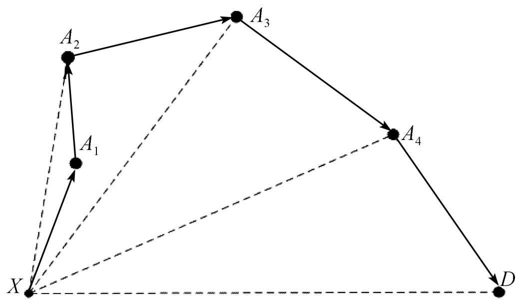


Figure 3. The case of concave polygon in perimeter routing

Specifically, node i selects the next-hop node k with the most residual energy from all its neighboring nodes which can make angle progress compared with the last hop.

Figure 4 is a typical example, in which X, A_1, B_1, $C_1$and D are the boundary nodes of the hole. The dotted circle is the upper bound of A_2's sending range. $X \rightarrow A_1 \rightarrow B_1 \rightarrow C_1 \rightarrow D$ is chosen as the route, following the pure right-hand rule. However, our new rule may adopt the path $X \rightarrow A_2 \rightarrow B_2 \rightarrow C_2 \rightarrow D_2 \rightarrow D$ according to the energy conditions of these nodes. For example, X finds that both A_1 and A_2 can make angle progress, but the remaining energy of A_2 is more than A_1's. Therefore P is relayed to A_2. After that, similarly, in A_2's sending range, there are A_1, B_1 and B_2 that can enjoy angle progress. Although B_1 achieves the most angle progress, it has only a little power left. Thus, B_2, whose current energy is the greatest of these candidates, relays P from A_2.

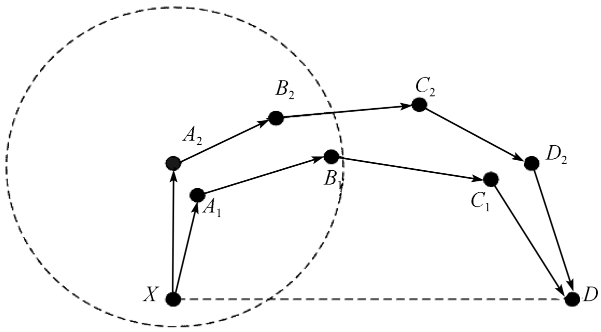


Figure 4. An example of new perimeter routing

As we know, the right-hand rule aims for the case which has no crossing links in the face. Hence, many routing protocols, such as GPSR, GOAFR+ and CLDP, use RNG or GG, to prune unnecessary links. Either approach can be employed in our new rule, and we use that of the GPSR in the simulation.

4 Simulation Results and Performance Evaluation

We used Network Simulation 2 (NS2)[19] to evaluate the performance of EGR. To compare EGR with prior work in location-based routing, we also simulated DREAM, LAR and GPSR protocols. DREAM and LAR are well-known protocols that adopt flooding, and it is necessary for us to compare them with EGR, which also uses flooding. We considered GPSR as a typical geographic routing, whose right-hand rule is modified in EGR's simulation. Therefore, we include GPSR in the performance comparison.

4.1 Basic simulation scenarios

In our simulation, the time intervals of the beacons and the global location updates were chosen to be 1s and 8s, respectively. We simulated 30 CBR traffic flows, originating from randomly-selected sending nodes. Each CBR flow sends at 1Kbps, and uses 64-byte packets. Each simulation lasts for 300 seconds of simulated time. We summarize the general simulation environment in Table 1.

Table 1. Simulation environment setting

MAC Layer	IEEE 802.11
Bandwidth	2Mbps
TERRAIN	(2000m, 2000m)
Node Number	100-300
Node Placement	Random
Radio Range	250m
Initial Energy	1000J
Transmission Power	1W
Received Power	0.375W

We define the lifetime of the MANET in this paper as the moment when the first node runs out of one fifth of its initial energy, because this would have led to a decrease of node density, which may have influenced the results of other performances.

4.2 Comparison between pure and energy-based right-hand rules

Before carrying out the routing simulation comparison, we need to validate the effect of our new right-hand rule on network lifetime. In this subsection, we add the pure and energy-based right-hand rules (PRHR and ERHR) to EGR's basic mode to assess their impact on lifetime.

Having outlined the basic settings in Section IV.A, the following gives the details ofother esimulation settings. A square node hole, whose four edges are all 800m, is set at the center. We position the 16 boundary nodes of the hole equally, so that the distance between every pair of nodes is 200m. Other nodes are located outside the hole randomly. We make all of the nodes static and set the hole to show the energy effect of ERHR.

Figure 5 shows a significant difference between the PRHR and ERHR results. When we applied the PRHR, each flow passing through the node hole will always consume the energy of the boundary nodes. The energy of these nodes soon becomes depleted. However, ERHR allows the flows traversing the hole to balance the energy consumption of nodes near the hole. Hence, ERHR extends the network lifetime by approximately 20%, compared with PRHR.

Figure 5 also shows that the network lifetime decreases as the node density increases. This is because energy consumption of each node, the expenditure of the receiving beacon for example, rises as network scales. This is inevitable for any routing that needs a beacon. Although beaconless routing can avoid this type of consumption, energy is consumed for data-packet and end-to-end packet delivery delay is longer. The reason is that every intermediate node transmits the data packet to all the nodes in a designated area and lets them wait for a period.

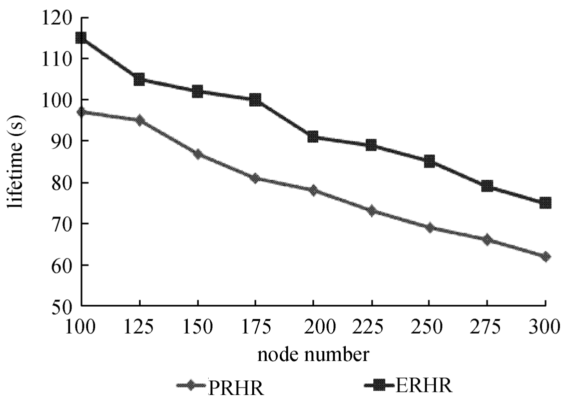


Figure 5. The network liftime of two right-hand rules

4.3 Simulation results of four routing protocols

Using the basic settings of Section IV.A, we compare the delivery ratio, end-to-end delay and lifetime of 4 different location-based routing protocols at different node densities. The settings are different from Section IV.B in that we do not set a node hole and all nodes are mobile. Each simulation was run for 300 s, and during this time, the mobile nodes moved in accordance with the random waypoint model. When the node reached its destination, it immediately moved to another position without pause. The average velocities of the nodes were 5, 10, 15, 20 and 25 m/s, specified in accordance with a normal distribution. Fig. 6, Fig. 7 and Fig. 8, show the impact of node density on the delivery ratio, the end-to-end delay and the lifetime.

Figure 6 demonstrates that when the node density is low, protocols with constrained flooding have a higher rate of delivering a packet successfully. This is because they have several relay nodes to serve during each hop. However, EGR and GPSR with a single path have difficulty choosing the next-hop node during forwarding. When the node density increases, EGR shows a graceful increase in delivery ratio.

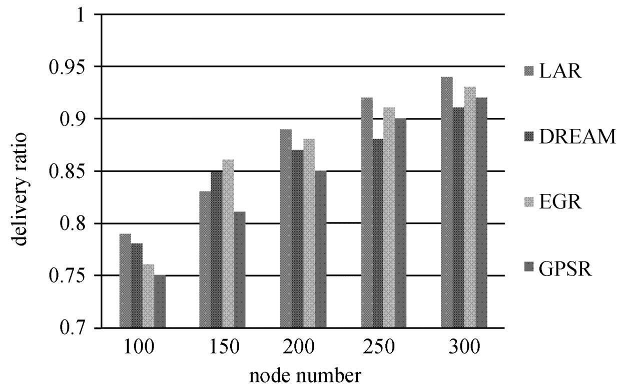


Figure 6. Delivery ratio for different algorithms when each node has a velocity of V = 10 m/s

Now we consider the relationship between node density and delivery ratio. It is obvious that in a low density network, there are fewer candidates for nodes to choose as the next hop. Sometimes, there are no path at all. Therefore, once a node has more neighbors, the packet is more easily relayed and the delivery rate increases.

In Fig.7, GPSR has the lowest delay due to its single-path feature that is nearly optimal. In each hop, data packets are relayed to the node closest to the destination. This means that GPSR achieves the most progress during every hop and a minimal total hop number. As node density goes up, GPSR has a lower delay, since each relay node with more neighbors enables the selection of a neighbor that can make better progress. This results in a reduction of the hop number.

For LAR and DREAM which use constrained flooding in a large area, there are a number of collisions, waits and retransmissions, especially when an area of the network is busy. When node density increases, these routing protocols make each packet go through too many nodes, which creates a heavy load, a long delay and even canceled transmission of some packets. Moreover, the LAR protocol requires the finding of a route before sending packets. All the above factors lead to a longer delay.

In EGR, with the increasing node density, the number of neighbor nodes for the intermediate nodes increases. It may make the nodes for the next-hop nearer to the intermediate nodes, which introduces a slightly higher delay. However, as a result of the restriction in the forwarding area, this probability is relatively low. From the results, we can conclude that EGR does not increase end-to-end delay due to the influence of energy awareness on forwarding.

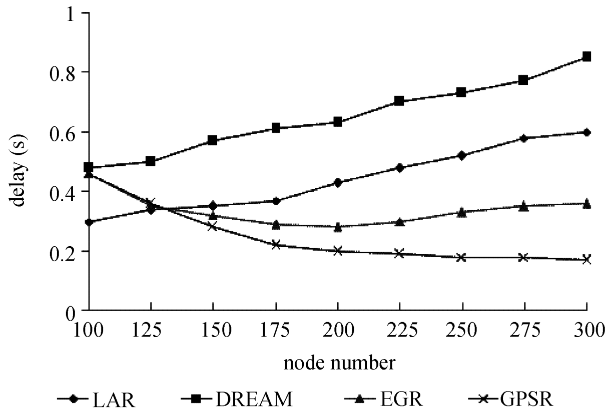


Figure 7. End-to-End delay for the different algorithms when each node has a velocity of V=15 m/s

Figure 8 shows that EGR has the longest lifetime. Constrained flooding in the LAR and DREAM protocols leads to higher energy consumption. Therefore their lifetime is fairly short. This disadvantage becomes more visible with increasing node density. GPSR always chooses some nodes as intermediate nodes. These nodes will "die" early, negatively impacting the network lifetime. Although the end-to-end delay of EGR is a little longer than that of GPSR, our objective is to present a routing protocol that enables a longer network lifetime and that also has other favorable performance parameters.

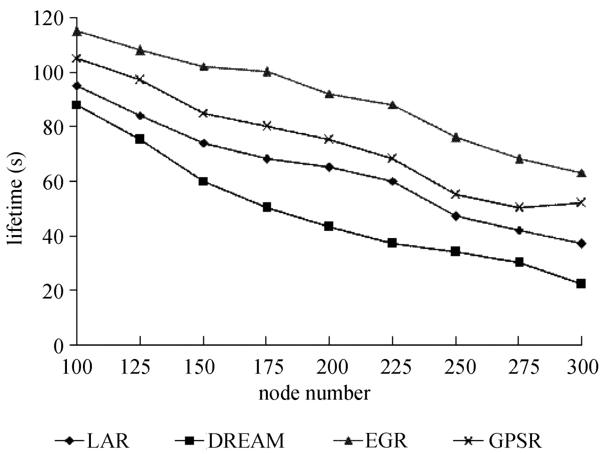


Figure 8. Network lifetime for different algorithms when each node has a velocity of V = 20 m/s

GPSR enjoys a minimal hop count, which means minimal total energy consumption. On the other hand, EGR averages the consumption, while it consumes more energy in total. The key issue is which of these two protocols is more effective for prolonging the network lifetime. The results in Fig.8 are convincing proof that EGR's energy awareness mechanism plays an important role in achieving a longer lifetime than GPSR does.

For networks with low-speed nodes, EGR can deliver packets without constrained flooding. On the other hand, the constrained flooding is an effective measure for EGR to guarantee a high delivery ratio when the nodes move fast. Consequently, we can apply EGR to networks with different node speeds as demonstrated by the results shown in Fig.9.

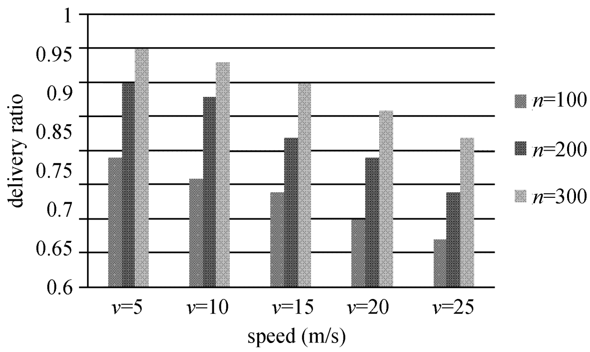


Figure 9. Percentage of data packets delivered, when nodes move at five different speeds

As nodes become more mobile, the delivery ratio falls. This can be intuitively explained. For instance, node i receives the latest beacon from its neighbor node j at t_0(the beacon cycle is T). At t_1 ($t_1 - t_0$¡ T), i relays a packet to j. Unfortunately, j may have moved out of the sending range of i and misses it. The more quickly the nodes move, the more likely this sort of incidents will be.

5 Conclusion

In this paper, we have proposed a novel routing protocol for MANET, the Energy-Aware Geographic Routing (EGR) protocol, that combines greedy routing, energy awareness routing and constrained flooding. This protocol effectively prolongs the network lifetime as well as provides an acceptable delivery ratio and end-to-end delay.

For future work, we plan to study algorithms that are more applicable to energy-aware routing to solve the "void" problem. Since quite a number of studies are specific to static wireless sensor networks (WSNs), we can add more factors that adapt to MANET for energy-aware routing protocols, and this could make energy-aware approaches more useful.

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