

Regional Route Maintenance Protocol Based on Local Pheromone Diffusion for Mobile Ad Hoc Networks

Hyun-Ho Choi¹ · Bongsoo Roh² · Myounghun Han² · Jung-Ryun Lee³

© Springer Science+Business Media, LLC 2017

Abstract Route maintenance protocol has a tradeoff between the amount of control overhead and the provision of useful alternative paths. To break through this tradeoff, we consider a bio-inspired approach based on the natural phenomena of ant pheromone. The pheromone is accumulated on the shortest path between the nest and the food, and then diffused into its vicinity over time. Thus, the ants can find another route along this locally diffused pheromone when the shortest path in use is blocked. Based on this local pheromone diffusion and rerouting behavior, we propose a new route maintenance protocol for mobile ad hoc networks. First, pheromones (i.e., routing information) are locally diffused around the shortest path between

the source and the destination (i) by overhearing at the one-hop neighbors from the shortest path and (ii) by sharing the overheard pheromone information among the one-hop neighbors. Thereafter, a probabilistic path exploration is executed within the one-hop region based on the locally diffused pheromone and so useful alternative paths around the shortest path are discovered. Through intensive simulations, we verify that the proposed regional route maintenance protocol outperforms the conventional routing protocols in terms of disruption frequency, delivery ratio, delay, and jitter, while reducing the control overhead.

Keywords Routing protocol · Route maintenance · Bio-inspired routing · Pheromone diffusion · Mobile ad hoc network

A part of this paper was presented at the International Conference on Bio-inspired Information and Communications Technologies (BICT) 2015 [1].

✉ Jung-Ryun Lee
jrlee@cau.ac.kr

Hyun-Ho Choi
hhchoi@hknu.ac.kr

Bongsoo Roh
saintroh@add.re.kr

Myounghun Han
mengddor@add.re.kr

¹ Department of Electrical, Electronic and Control Engineering, Hankyong National University, Anseong 17579, South Korea

² The 2nd R&D Institute, Agency for Defense Development, Daejeon 34186, South Korea

³ School of the Electrical Engineering, Chung-Ang University, Seoul 06974, South Korea

1 Introduction

Mobile ad hoc networks (MANETs) have a highly dynamic topology because of node mobility, impairments of wireless media, scarce radio resource, limited node energy, and so on. In such a dynamic environment, the route maintenance protocol, which updates and extends the routing table of each node during the communication, is very important to prevent the disruption of the path currently being used and provide a better path according to the topology change. However, gathering the topology information for route maintenance causes a significant overhead. Therefore, there exists a tradeoff between the amount of control overhead and the provision of useful routing path in the route maintenance protocol [2].

For example of proactive routing protocols, such as destination-sequenced distance vector (DSDV) [3] and optimized link state routing (OLSR) [4], all nodes in the

network broadcast their routing table information periodically. Thus, the routing information is updated continuously during the communication, but the transmission of control packets increases in proportion to the number of nodes in the network. On the other hand, in the case of reactive routing protocols, such as ad hoc on-demand distance vector (AODV) [5] and dynamic source routing (DSR) [6], they do not generate any control packet for route maintenance during the communication, but find a route through the flooding mechanism only when the path being used is broken. Therefore, there is no overhead before a link failure, but the update to a better route is impossible during the communication and also the flooding overhead is much greater in a dynamic topology that causes frequent link failures.

To overcome such tradeoff issue in the route maintenance, in this paper, we consider a bio-inspired approach based on the natural phenomena of ant pheromone, i.e., accumulation, evaporation, attraction, and diffusion [7, 8]. The pheromone is accumulated along the ants' moving paths between their nest and a food. At the same time, the pheromone is evaporated so that more pheromones remain on the shorter path. Moreover, the higher concentration of pheromone attracts more ants so that the majority of the ants move along the shortest path after a certain period of time. In addition, the pheromone is chemically diffused around. So, the pheromones are concentrated on the shortest path and its surrounding as time goes. Consequently, the ants can find another route along the diffused pheromones around the shortest path if the shortest path in use is blocked [9, 10].

The conventional bio-inspired routing protocols have mainly considered the former three principles of pheromone (i.e., accumulation, evaporation, and attraction) to find the shortest path focusing on the route setup process [11]. In addition to these three, in this paper, we consider the principle of pheromone diffusion focusing on the route maintenance process. The proposed route maintenance protocol diffuses the pheromone information¹ locally around the shortest path between the source and the destination, and then maintains available routing paths within the pheromone-diffused region. For the pheromone diffusion, the neighbor nodes with one-hop distance from the shortest path overhear the routing information that is sent over the shortest path and share it among themselves. For the route maintenance, a probabilistic path exploration is executed along the locally diffused pheromone so that useful alternative paths are discovered around the shortest path. This regional route maintenance concept based on the local pheromone diffusion can provide useful routing

paths although it does not consider all possible paths in the network, while significantly reducing the control overhead.

The rest of this paper is organized as follows: Section 2 reviews the related bio-inspired routing protocols based on the principles of pheromone. Section 3 describes the motivation of the proposed scheme and shows preliminary results to validate our hypotheses. Section 4 explains the operation of the proposed route maintenance protocol in detail. Section 5 presents the performances of the proposed protocol according to the node mobility and the network scale. Finally, Section 6 concludes this study.

2 Related bio-inspired routing protocols

On the basis of the natural phenomena of ant pheromone, a number of different bio-inspired routing protocols have been proposed [11–25]. Initial routing protocols have been developed under the assumption of static topology in wired networks. A representative routing protocol is AntNet [12], which has first applied the basic three principles of pheromone to the packet switched data networks in order to find a shortest path between the source and the destination. On the basis of this AntNet protocol, several enhanced protocols have been proposed by modifying the behavior of ant packets, in order to (i) reduce the path setup time [13], (ii) avoid the formation of routing loop [14], (iii) prevent the stagnation of pheromone [15], or (iv) guarantee the quality of service (QoS) of traffic [16]. In these routing protocols, the alternative routing paths between the source and the destination are naturally formed by the exploration of ant packets, which is proportional to the amount of accumulated pheromone in general or is totally random in some cases. Namely, these works did not **consider** a separate route maintenance protocol because they assumed a wired network with less dynamics.

Needs of route maintenance protocols have been raised in wireless networks with more dynamic topology (e.g., MANET). To find alternative paths, some protocols use so-called uniform ants that wander through the network choosing each next hop according to a uniform distribution [17, 19]. The use of the uniform ants provides various route information without significant overhead in a dynamic topology, but often offers inefficient alternative paths because the uniform ants randomly explore the network. To solve this inefficiency, the reactive approach like AODV has been applied to the bio-inspired routing protocols [20, 22]. In such protocols, ant flooding occurs only when existing routing information is out of date or the QoS requirement of the path being used cannot be satisfied anymore. This ant flooding can find another shortest path, but may induce a considerable flooding overhead and the service disruption during the period of flooding.

¹The pheromone information is a stochastic value to estimate the goodness of the route and is inversely proportional to the distance vector. Its use is a key feature of bio-inspired routing protocols [7].

As a hybrid protocol, the representative bio-inspired routing protocol is AntHocNet, which has first introduced a concept of *pheromone diffusion* for the route maintenance [23, 25]. For the pheromone diffusion, AntHocNet uses a similar process of DSDV. That is, all the nodes in the network periodically broadcast *hello* messages containing the pheromone information. On receiving this *hello message*, the adjacent nodes derive a new pheromone for themselves and further forward it in their own periodic broadcasts. The pheromone obtained by this pheromone diffusion is called a virtual pheromone and is managed separately. Based on this diffused virtual pheromone, AntHocNet finds available alternative paths for a certain communication session. To this end, the source node periodically sends out proactive forward ants toward its destination. The proactive forward ants probabilistically explore the routes that have emerged from the virtual pheromone. Once a proactive forward ant reaches the destination, it is converted into a proactive backward ant that travels back to the source and leaves the regular pheromone along the path. This regular pheromone is used to reliably forward data packets. In this way, the pheromone diffusion offers possible routes and the proactive ants explore these routes to find available alternative paths between the source and the destination.

However, the pheromone diffusion in AntHocNet may cause a large overhead when there are many nodes in a network because all the nodes in the network must periodically transmit hello messages including the pheromone information. In addition, each hello message should contain the pheromone information for multiple destinations; thus, the size of hello message may increase as the network scale is larger. Further, the proactive ant exploration in AntHocNet may not operate well in a highly dynamic or large-scale network because its pheromone diffusion basically follows the bootstrapping algorithm of DSDV. That is, the convergence of pheromone information becomes more difficult as the node mobility and the number of nodes increase. Consequently, inaccurate pheromone information may be diffused throughout the network so that the proactive ants may not find useful alternative paths. In our study, we design a new route maintenance protocol to overcome these weaknesses of previous routing protocols.

3 Motivation and pre-verification

The proposed route maintenance protocol is motivated by a pheromone diffusion and rerouting behavior of real ants in nature. It is well-known that ants can find the shortest path between the nest and the food by the principles of pheromone: accumulation, evaporation, and attraction. Moreover, it is observed that the accumulated pheromone is chemically diffused around the shortest path over time.

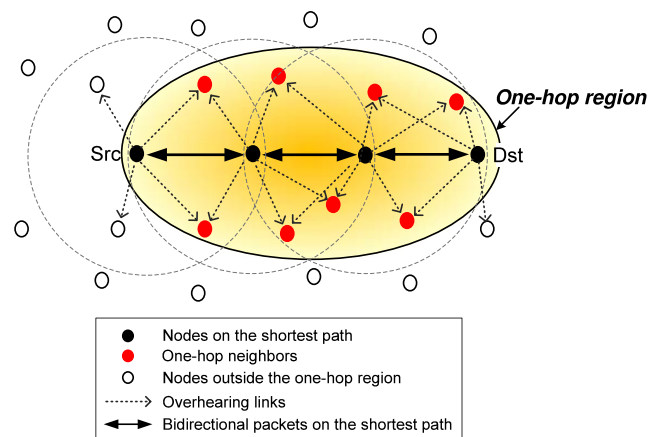


Fig. 1 Concepts of one-hop neighbor and one-hop region

Thus, if the shortest path being used is blocked by an obstacle, the ants try to find a new alternative path along this diffused pheromone in the vicinity of the used shortest path [9, 10]. This pheromone diffusion and rerouting behavior is so natural that the broken route can be reestablished promptly and the newly connected path can be near-optimal because it is found near the previous shortest path.

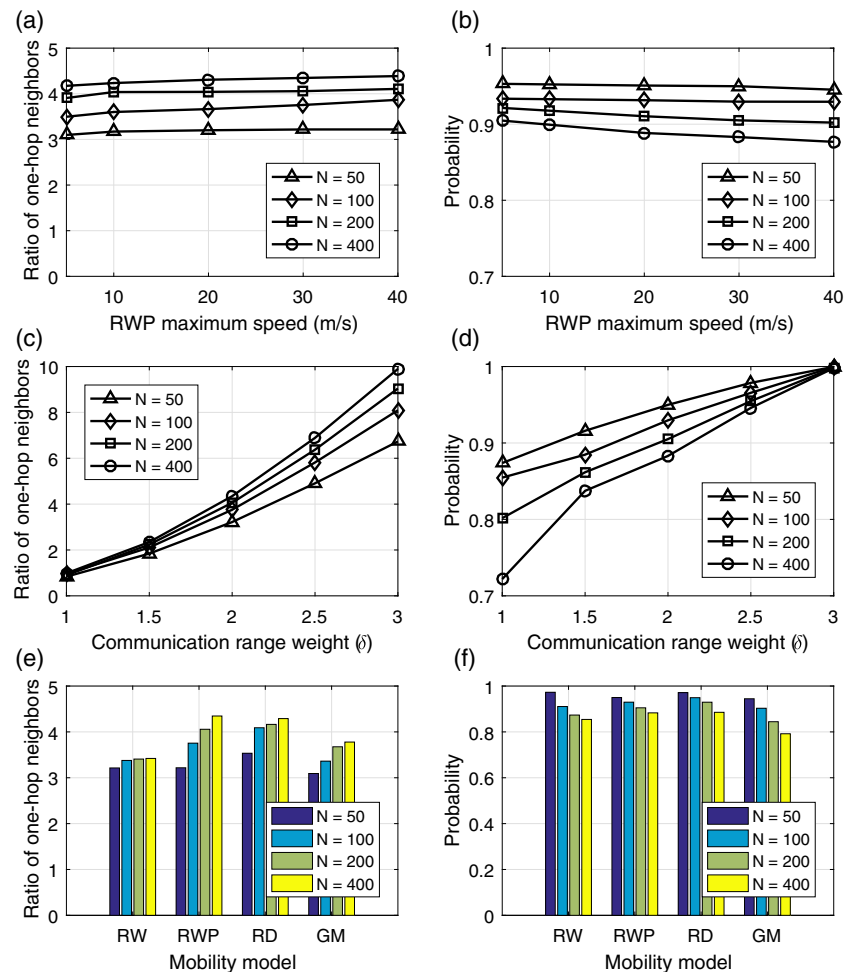
To realize such a pheromone diffusion and rerouting behavior of real ants in MANETs, we first adopt a overhearing technique based on the broadcast nature of wireless media. The nodes located in the vicinity of a certain routing path can overhear some packets transferred back and forth on that path. These nodes can derive pheromone information from those overheard packets without overhead. We call such overhearing nodes *one-hop neighbors*² and define the network area where the one-hop neighbors exist as *one-hop region*, as shown in Fig. 1. That is, the one-hop region covers all the one-hop neighbors of each intermediate node on the discovered routing path. Thereafter, additional pheromone diffusion performs within the one-hop region as the one-hop neighbors share the overheard pheromone information with one another. Therefore, the plentiful pheromone information are locally diffused around the shortest path between the source and the destination. Then, available alternative paths are discovered within this one-hop region so that the transmitting packets are rerouted to those alternative paths if the shortest path being used is broken.

To make this concept effective in MANET environments, we first need to verify two hypotheses as follows:

- There exist one-hop neighbors to offer alternative paths around the shortest path between the source and the destination in MANETs.

²Details on how to determine the one-hop neighbors will be explained in Section 4.2.

Fig. 2 Verification of two hypotheses in MANETs: ratio of one-hop neighbors and probability that the new shortest path is found within the one-hop region according to mobility level (a, b), communication range (c, d), and mobility model (e, f)



- When the shortest path currently being used is broken, the next shortest path is found within the one-hop region with high probability in MANETs.

To verify these two hypotheses, we have performed a preliminary experiment in a general MANET environment. To this end, the representative statistical mobility models used for MANET simulations, such as random walk (RW), random waypoint (RWP), random direction (RD), and Gauss-Markov (GM) mobility models, are considered [26, 27]. The random network topology (i.e., uniform node distribution) is assumed and the communication range of the nodes is set to $\delta W/\sqrt{N}$ where δ is a weighting factor to adjust the communication range,³ W is the length of one side of square network area and N is the number of nodes in the network [28]. We simply consider one communication session and select a source node and a destination node randomly. We experiment to investigate how many one-hop neighbors exist around the shortest path and how possibly

the next shortest path is found within the one-hop region when the current shortest path is broken, according to the network scale (i.e., the number of nodes in the network), the mobility level (i.e., the maximum speed of nodes in the RWP model), the communication range weight (δ), and the four mobility models.

Figure 2 shows two performance metrics: the ratio of one-hop neighbors, which is defined as the ratio of the number of the one-hop neighbors to the number of nodes on the current shortest path, and the probability that the new shortest path is found within the one-hop region when the shortest path being used is broken. To verify two hypotheses in various MANET environments, we consider the variations in the number of nodes in the network (N), RWP maximum speed, communication range weight (δ), and mobility models. We use the RWP mobility model, the RWP maximum speed of 30 m/s, and $\delta = 2$, as default, unless otherwise noted. The results show that both the ratio and the probability are not significantly affected by the mobility level and mobility models, but they are obviously affected by the communication range. That is, both performances decrease as δ decreases. Meanwhile, the ratio of one-hop neighbors

³In general, δ is set to a value between 1.5 and 2 because too small δ can cause network partitioning and too large δ can cause more collisions and interference in the network [28, 29].

increases but the probability decreases as N increases. As N increases, the absolute number of one-hop neighbors increases so that the ratio of one-hop neighbors increases. However, the relative number of one-hop neighbors to the total number of nodes (N) decreases, which increases the probability that the newly discovered shortest path includes a node that is not the one-hop neighbor.

In summary, the results in Fig. 2 exhibit that there exist one-hop neighbors to offer alternative paths around the shortest path, i.e., the ratio of one-hop neighbors is greater than 2 regardless of the number of nodes, mobility level, and mobility model when the practical value of δ that ranges from 1.5 to 2 is employed. Moreover, the probability that the new shortest path is found within the one-hop region maintains a high level greater than 0.8 when $\delta \geq 1.5$. On the basis of these two results, our two hypotheses are verified and our bio-inspired approach can be effectively applied to the MANET environment.

4 Proposed route maintenance protocol

The proposed route maintenance protocol consists of two processes: *local pheromone diffusion* and *regional route maintenance*. The local pheromone diffusion process is performed to diffuse the pheromone information around the shortest path between the source and the destination, which consists of two subprocesses: the overhearing of exploitation ants and the sharing of overheard pheromone. On the other hand, the regional route maintenance process is performed to maintain the current shortest path and find useful alternative paths based on the diffused local pheromones, which also consists of two subprocesses: the exploitation of the shortest path and the exploration of alternative paths.

To support these processes, we design two types of ants as follows:⁴

- *Exploitation ant*: This ant is used to exploit the current shortest path for the maintenance of shortest path and also is intended to be overheard by one-hop neighbors around the shortest path for the local pheromone diffusion. The source periodically generates the forward exploitation ant and this ant moves forward to the destination along the best direct pheromone. If the destination receives this forward exploitation ant, it generates the backward exploitation ant as a response and this ant goes back to the source along the best direct pheromone as well. That is, these forward and backward exploitation ants move back and forth along the shortest path between the source and the destination. Each exploitation ant contains the information such as source

address, destination address, sequence number, and the total cost from the originating node to the current node.

- *Exploration ant*: This ant is used to explore alternative paths around the shortest path. The source generates the forward exploration ant whenever it receives the backward exploitation ant, and this ant moves forward to the destination probabilistically in proportion to the locally diffused pheromone within the one-hop region. If the destination receives this forward exploration ant, it generates the backward exploration ant as a response and this ant goes back to the source exactly along the reverse of the path through which the forward exploration ant has passed. Each exploration ant contains the information such as source address, destination address, sequence number, the total cost from the originating node to the current node, and the addresses of nodes through which the forward exploration ant has passed.

Furthermore, we classify the pheromone information obtained by two processes into two types, as follows:

- *Indirect pheromone*: This pheromone is formed by the process of local pheromone diffusion and so provides indirect possibility to reach the destination. The indirect pheromone is used by only the exploration ants to find the alternative paths.
- *Direct pheromone*: This pheromone is formed by the process of regional route maintenance. That is, the direct movement between the source and the destination of the exploitation ants updates the prior direct pheromone, and also that of the exploration ants changes the indirect pheromone to the direct pheromone. Therefore, this direct pheromone secures the end-to-end transmission between the source and the destination; thus, it is used to forward data packets and exploitation ants.

Now we explain the detailed operations of the proposed route maintenance protocol with respect to (i) routing table structure, (ii) local pheromone diffusion, (iii) regional route maintenance, and (iv) link failure and rerouting.

4.1 Routing table structure

Figure 3 shows an example of a routing table for a node that manages the information for the destination node d in the proposed protocol. Basically, the routing table records the multiple-path information for one destination. In addition to the typical information managed in the existing routing table, the proposed protocol adds new information such as update time, pheromone, and type. The role of each information is as follows:

- *Next*: It indicates the next node to which the packet can be forwarded.

⁴Agent packets used for control in the bio-inspired routing protocols are often called ant.

Fig. 3 An example of routing table in the proposed protocol

Dst	Next	Cost	Seq. Num.	Update Time	Pheromone	Type
d	a	4	10	09:29:45	0.33	Direct
	b	6	11	09:30:00	0.28	Direct
	c	7	9	09:28:20	0.14	Direct
	x	5	n/a	09:29:00	0.21	Indirect
	y	9	n/a	09:28:30	0.11	Indirect
	z	10	n/a	09:26:15	0.005	Indirect

Selected to forward the data and exploitation ant

Selected to forward the exploration ant with a high probability

- *Cost*: It represents the total cost consumed to transmit a packet to the destination over the next node. The cost can be defined using various metrics, such as the number of hops, delay, received signal strength, and bandwidth [30]. Here, we use the number of hops as a cost metric.
- *Sequence Number*: It is used to prevent duplicate updates from the same agent packet. It is set to the sequence number contained in the received agent packet only if the newly received sequence number is greater than the previously recorded sequence number.
- *Update Time*: It registers the time when the corresponding routing information is updated.
- *Pheromone*: It indicates the suitability of the next node in delivering a packet to the destination. The value of pheromone is inversely proportional to the cost and also decreases over time by considering its evaporation. In this study, we define the pheromone τ_{ij}^d for the route from a node i over the next node j to reach the destination d as

$$\tau_{ij}^d = \left(\frac{1}{c_{ij}^d} \right)^\alpha \left(\frac{1}{t_{ij}^d} \right)^\beta \quad (1)$$

where c_{ij}^d and t_{ij}^d denote the cost and the elapsed time (= current time – update time) for the corresponding route, respectively, and $\alpha \geq 1$ and $\beta \geq 1$ represent the weighting factors.

- *Type*: It indicates the type of pheromone and is set to either indirect or direct. The direct type is changed to the indirect type if the time of T_{direct} has passed since the update time, and also the row with indirect type is deleted if the time of $T_{indirect}$ has passed since the update time.

As explained, the direct pheromone is used to forward the data and exploitation ant, and the indirect pheromone is used to forward the exploration ant. Therefore, for the example in Fig. 3, the data packet and the exploitation ant destined for d are forwarded to the next node a because the pheromone to a is the highest in the direct pheromones. On the other hand, the exploration ant is likely to be forwarded

to the next node x with a high probability in proportion to the pheromone values with the indirect type. Details on how to select the next hop are provided in Section 4.3.

4.2 Local pheromone diffusion

Figure 4 illustrates the operations of local pheromone diffusion. After the initial route setup,⁵ the direct pheromone is formed along the shortest path between the source and the destination, and data packets are transferred along this direct pheromone. Further, the source periodically generates a forward exploitation ant and this ant is forwarded to the destination along the best direct pheromone. When it arrives at the destination, the destination generates a backward exploitation ant, and this ant is delivered back to the source along the best direct pheromone as well. These forward and backward exploitation ants are periodically exchanged between the source and the destination along the shortest path.

As shown in Fig. 4a, every node in the network can overhear the forward and backward exploitation ants that move along a certain shortest path. The nodes that overhear both the forward and the backward exploitation ants for the same source-destination (s-d) pair during a predetermined time $T_{overhear}$ become the one-hop neighbors of that s-d path. From the overheard exploitation ants, the one-hop neighbors can obtain a new routing information for the destination. If a one-hop neighbor i overhears the backward exploitation ant from the node j on the shortest path with the destination d , the total cost of the route from i to d over j , c_{ij}^d , is set to the sum of the cost from j to d , c_j^d , and the link cost from i to j , c_i^j (i.e., $c_{ij}^d = c_j^d + c_i^j$). Here, c_j^d is obtained from the overheard exploitation ant and c_i^j can be previously known by *hello* messages that are periodically broadcasted to check the availability of local links. Accordingly, the other information about the update time and the pheromone are determined and the type is set to ‘indirect’ in this case. In this way, the first local pheromone diffusion

⁵In this study, the same flooding mechanism as AODV is used for the fast initial route setup.

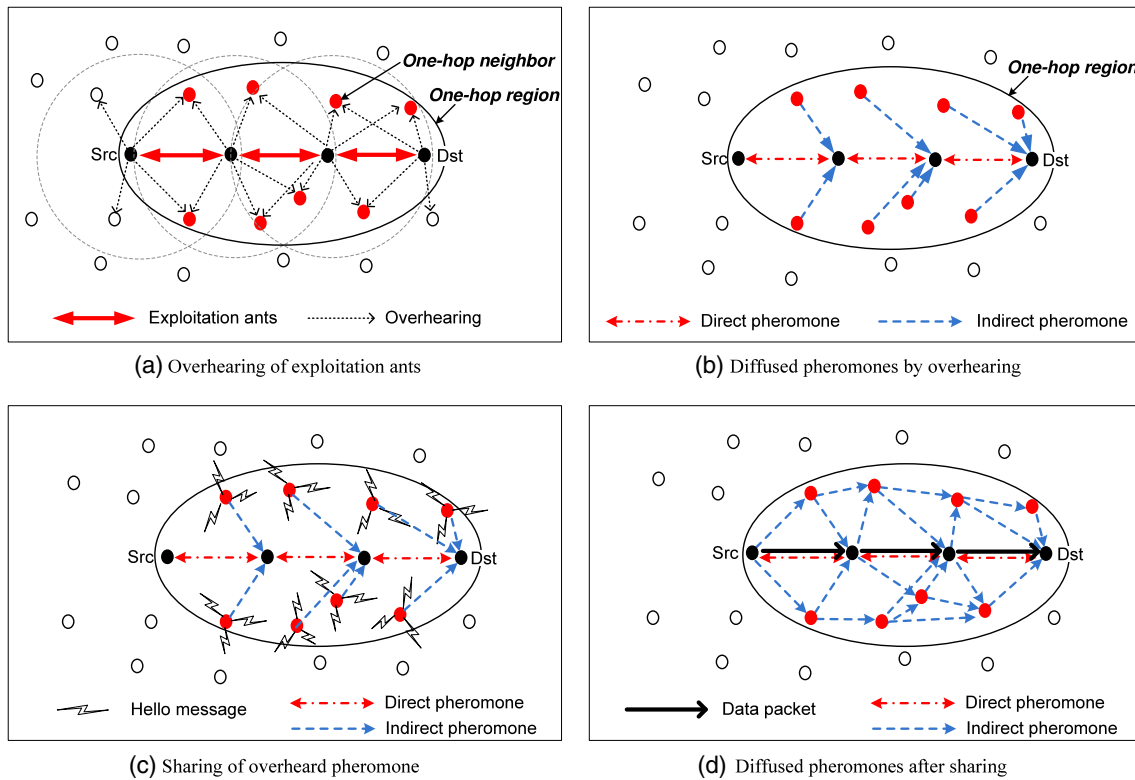


Fig. 4 Operations of local pheromone diffusion

is achieved by overhearing the exploitation ants. Figure 4b shows the indirect pheromones diffused by overhearing.⁶

After the overhearing subprocess, the second local pheromone diffusion is achieved by sharing the overheard pheromone information among the one-hop neighbors. As shown in Fig. 4c, each of one-hop neighbors locally broadcasts its best pheromone information (i.e., the highest one among indirect and direct pheromones) for each destination to share it with the other one-hop neighbors. This pheromone information can be included in the hello message to avoid the transmission of separate control packets. Further, the hello message can contain multiple pheromone information at once if a node has overheard from multiple s-d pairs. If a one-hop neighbor i receives this hello message from the other one-hop neighbor j , it updates the cost value for the corresponding destination d by using $c_{ij}^d = (\tau_j^d)^{-1} + c_i^j$ (like the bootstrapping in DSDV) where τ_j^d denotes the highest pheromone value from j to

⁶It is worth noting that the periodic exchange of forward and backward exploitation ants can be omitted if the data packets are transmitted bidirectionally or the end-to-end acknowledgement packets are generated from the destination, with the inclusion of the total cost value in their headers like the exploitation ant. In this case, the local pheromone diffusion is possible without the periodic transmission of exploitation ants; thus, reducing the overhead.

d included in the received hello message. Note that normal nodes outside the one-hop region are not involved in this local pheromone diffusion process. Figure 4d shows the locally diffused pheromones within the one-hop region after sharing the overheard pheromone. Such pheromone information is set to 'indirect' because the overheard or shared information is unreliable due to channel error and access collision. Thus, it provides indirect possibility to reach the destination.

4.3 Regional route maintenance

Figure 5 illustrates the operations of regional route maintenance, which consists of the exploitation of the shortest path and the exploration of alternative paths. First, the exploitation of the shortest path aims at maintaining the shortest path all the time because the cost of links consisting of the current shortest path varies with the topology change. To this end, the source periodically generates the forward exploitation ant and this ant is forwarded to the destination along the best direct pheromone. If the destination receives the forward exploitation ant, it generates the backward exploitation ant and also this ant is forwarded back to the source along the best direct pheromone. Through this periodic exchange of exploitation ants, the intermediate nodes on the shortest path can update their routing table to the newest

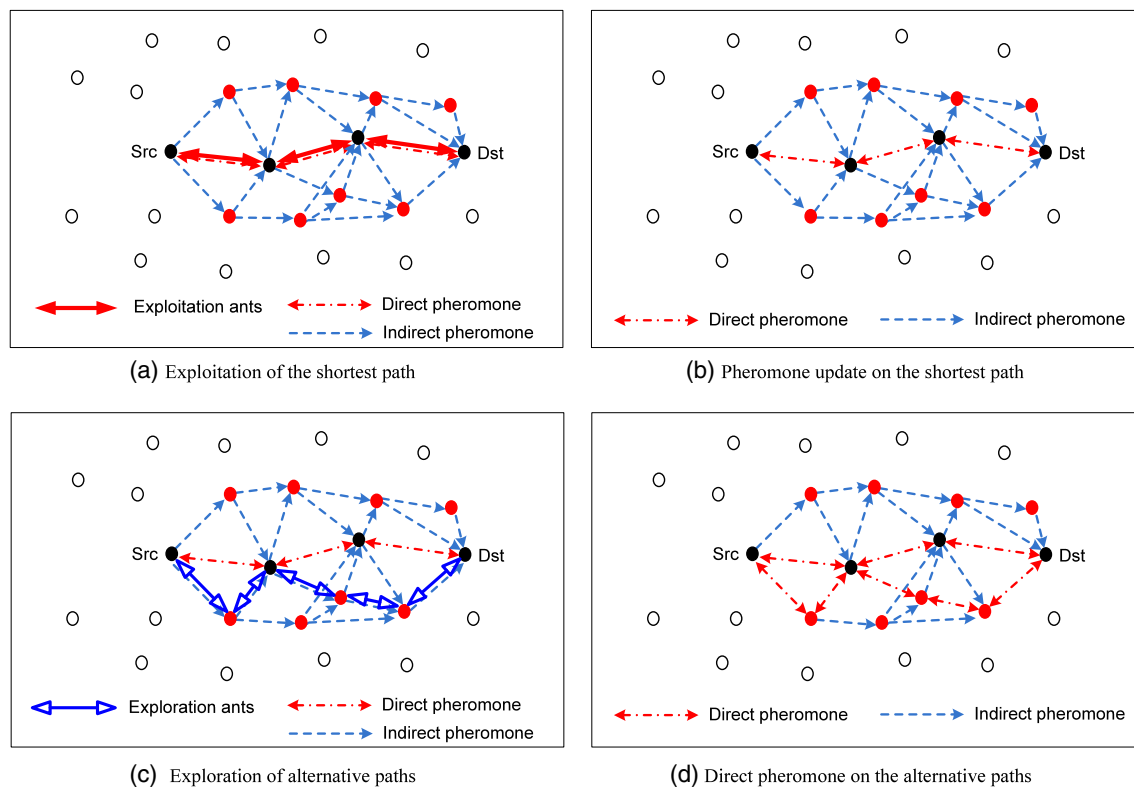


Fig. 5 Operations of regional route maintenance

information continuously.⁷ Figure 5a shows the movement of the exploitation ants between the source and the destination and Fig. 5b shows the updated direct pheromone on the shortest path accordingly.

On the other hand, the exploration of alternative paths aims at finding useful alternative paths around the shortest path based on the diffused local pheromone. To this end, the source generates the forward exploration ant whenever it receives the backward exploitation ant. This forward exploration ant is forwarded to the destination by selecting the next hop probabilistically in proportion to the indirect pheromones by using the following equation:

$$P_{in}^d = \frac{(\mu_{in}^d)^\gamma}{\sum_{j \in N_i^d} (\mu_{ij}^d)^\gamma}, \gamma \geq 1 \quad (2)$$

where P_{in}^d denotes the probability that node i chooses node n as the next hop for destination d , μ_{ij}^d represents the indirect pheromone value for the route from i over j to reach d , N_i^d indicates the set of neighbors of i over which an indirect pheromone is known, and γ denotes a parameter value that can control the exploratory behavior of the ants. Unlike the exploitation ant, the forward exploration ant records

the address of the intermediate nodes—through which it arrives at the destination—in its header. If the destination receives the forward exploration ant, it generates the backward exploration ant and this ant is delivered to the source exactly along the reverse of the path through which the forward exploration ant has passed. Through this exchange of exploration ants, the intermediate nodes on that alternative path can update their routing table and set the type to ‘direct’. That is, the indirect pheromones are changed to the direct pheromones by this end-to-end path exploration. Figure 5c shows the movement of the exploration ants between the source and the destination and Fig. 5d shows the direct pheromone formed on the found alternative paths accordingly.

4.4 Link failure and rerouting

Figure 6a illustrates an example when a link failure occurs by the movement of a node. If a node detects a link failure, it deletes the corresponding routing table information and notifies this link failure to its neighbors again only if it has no more next-hop information for the corresponding destination. Otherwise, the node does not need to proceed this notification because it has another alternative route information to reach the destination. Since the proposed route maintenance protocol has found some alternative paths

⁷Note that the exchange of exploitation ants also plays an important role for the local pheromone diffusion by overhearing, as described in Section 4.2.

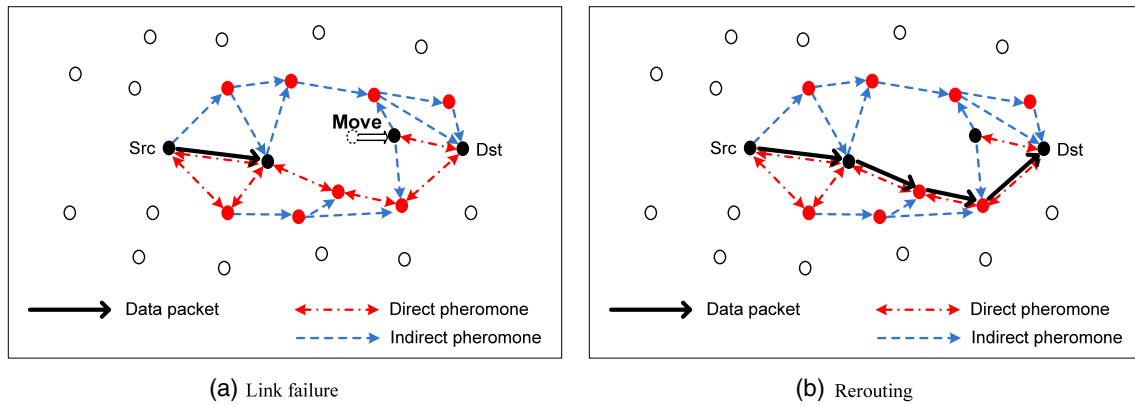


Fig. 6 Operations of link failure and rerouting

beforehand, the data is forwarded to the other route automatically along the next highest direct pheromone in the case of link failure, as shown in Fig. 6b. In this way, the seamless rerouting is achieved without the disruption of data transmission.

4.5 Finite state machine

Figure 7 shows a finite state machine (FSM) representation of the proposed route maintenance protocol. Each node is started up in its initial state in which the related parameters are initialized. Then, it moves to its idle state where it waits for events to happen. The events take place by the arrival of packets, such as data, ants, and hello, and the expiration of timers.

In case of a data packet reception event, the node forwards the data to the next hop after the lookup of routing table if it is an intermediate node. On the other hand, if it is a destination node, it delivers the data to the application layer.

In case of an ant packet reception event, the routing table is first updated based on the information of the received ant packet. Then, the operation is different according to the type of ant. In case of the forward exploitation ant, the node forwards this ant to the next hop if it is an intermediate node; generates a backward exploitation ant as a response if it is a destination node; or sets a timer $T_{overhear}$ if it has overheard this ant. In case of the backward exploitation ant, the node forwards this ant to the next hop if it is an intermediate node; generates a forward exploration ant if it is a source node; or includes the best pheromone information in

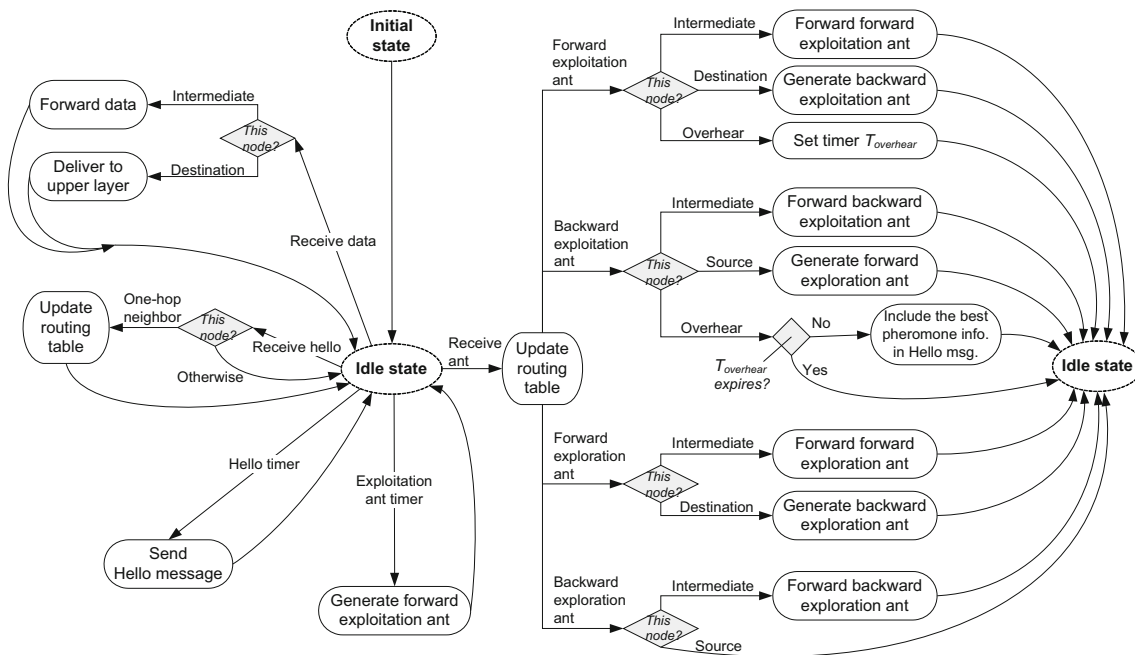


Fig. 7 Finite state machine of the proposed route maintenance protocol

a hello message if it has overheard this ant before the timer $T_{overhear}$ expires. In case of the forward exploration ant, the node forwards this ant to the next hop if it is an intermediate node, or generates a backward exploration ant as a response if it is a destination node. In case of the backward exploration ant, the node forwards this ant to the next hop if it is an intermediate node, or does nothing if it is a source node.

In case of a hello packet reception event, the node updates the routing table if it is a one-hop neighbor. Otherwise, it does not update the routing table.

The different timer events are scheduled by the node itself. Hello timer events are scheduled at regular intervals during the period that the node is involved in the route maintenance process. Reception of a hello timer event provokes the node to send a hello message that includes the best pheromone information. Exploitation ant timer events are also scheduled at regular intervals from the moment a session is started to the end of it. Reception of an exploitation ant timer event leads the node to send out a forward exploitation ant.

5 Results and discussions

In this section, we first describe the simulation environments, and then, present the simulation results according to the variations of node mobility and network scale.

5.1 Simulation environments

For performance evaluation, we used an OPNET simulator with simulation parameters, as summarized in Table 1 [31]. We consider a square network area with a width of 1000 m. The communication range of the nodes is set to $\delta W/\sqrt{N}$ where δ is a weighting factor and set to 2, W is the width of the network area and N is the number of nodes in this network [28]. Nodes move according to the RWP mobility model [32]. In the RWP model, each node starts from a randomly chosen position and independently chooses a random speed between a given minimum and maximum speed and a random pause time. We use a minimum speed of 0 m/s and vary the maximum speed from 5 to 40 m/s to control the mobility level. The pause time is chosen randomly between 0 and 30 s. Each experiment has a duration of 900 s and is repeated 100 times for averaging. Data traffic is assumed to be unidirectional UDP that does not require an acknowledgement. 10 unidirectional data sessions are run concurrently between randomly chosen source and destination nodes [25]. Each session starts randomly between 0 and 180 s after simulation starts, and all data sessions run till the end of the simulation. In each session, the source generates 4 data packets of 64 bytes per second. Moreover, the hello message and the forward exploitation

Table 1 Simulation parameters

Name	Value
Number of nodes (N)	50~300 (default=100)
Width = Height (W)	1000 m
Communication range	$\delta W/\sqrt{N}$ m ($\delta = 2$)
Mobility model	Random waypoint (RWP)
RWP minimum speed	0 m/s
RWP maximum speed	5~40 m/s (default=30)
Pause interval	Random[0,30] s
Simulation time	900 s
Number of simulations	100
Number of data sessions	10
Period of data packet generation	0.25 s
Period of hello message generation	1 s
Period of forward exploitation ant gen.	1 s
T_{direct}	2 s
$T_{indirect}$	2 s
$T_{overhear}$	1 s
Weighting factors	$\alpha = 2, \beta = 1$
Exploratory parameters	$\gamma = 5, \beta_1 = \beta_2 = \beta_3 = 20$ for AntHocNet
Size of data packet	64 bytes
Size of exploitation ants	24 bytes
Size of exploration ants	$24+4 \times (\# \text{ of transmission hops})$ bytes
Size of hello message	$20+8 \times (\# \text{ of overheard s-d pairs})$ bytes

ant are generated every second. The weighting factors (α , β) and the exploratory parameter (γ) are suitably chosen through many experiments. Details on how to select these parameters and the effect of the parameter changes on the performance are provided in Section 5.4.

For comparison, we consider representative ad hoc routing algorithms, such as AODV, multipath DSDV (MDSDV), and AntHocNet. AODV is a representative reactive routing protocol in MANETs so that most of the existing research use AODV as a benchmark. DSDV is a representative proactive routing protocol in MANETs. However, the original DSDV shows a bad performance in a dynamic topology; thus, we consider its multipath version, MDSDV, in which nodes construct their routing table to have multiple next-hop information for each destination [33, 34]. AntHocNet is a representative bio-inspired hybrid routing algorithm for MANETs as explained in Section 2. The parameters used for these competitive protocols are based on [25, 33]. For fair comparison, we used the same values in Table 1 for all the overlapped parameters, such as the basic simulation environment variables, the period of generation of all packets, and the size of all packets transmitted. Besides, the parameters for the exploratory behavior of the reactive ants,

proactive ants, and data packet used in AntHocNet, denoted as β_1 , β_2 , and β_3 , respectively, are all set to 20, as used in [25].

Here, we consider six different performance metrics as follows:

1. *Number of disruptions*: It indicates the number of occasions when there is no next-hop information for the data packet's destination in the routing table. This can mainly be caused by the dissipation of routing or pheromone information before being updated, or the disconnection of links due to the movement of nodes. The data packets can be lost owing to this disruption because we assume UDP sessions and so the lost data packet is not allowed to be retransmitted. Thus, the performance of disruption directly affects the performance of data delivery ratio. The number of disruptions can be used to not only identify the effects of both node mobility and network scale but also verify the performance of data delivery ratio.
2. *Data delivery ratio*: It is defined as the ratio of the number of correctly received data packets at the destination to the number of data packets sent from the source.
3. *End-to-end packet delay*: It indicates the average time taken by the data packets which are successfully delivered from source to destination. Because the delay of only successfully delivered packets are considered, the end-to-end packet delay directly indicates how short the routing path between the source and the destination has been found.
4. *Jitter*: It indicates the variation in the time interval between the arrivals of subsequent packets, and is defined as

$$\text{jitter} = \frac{\sum_{i=2}^n |(t_i - t_{i-1}) - (t_{i-1} - t_{i-2})|}{n - 2} \quad (3)$$

where t_i is the time of arrival of the i -th packet, and n is the total number of packets received at the destination during the communication. Jitter indicates the ability of the protocol to respond to network disruption smoothly as an important measure for QoS applications.

5. *Overhead in number of packets*: It is defined as the ratio of the total number of control packets transmitted by all the nodes in the network to the total number of data packets delivered to their destinations [25]. This indicates the average number of control packets required to successfully deliver one data packet from the source to the destination.
6. *Overhead in number of bytes*: It is defined as the ratio of the total bytes of control packets transmitted by all the nodes in the network to the total bytes of data packets delivered to their destinations. This represents the average bandwidth required by each node to transmit

the control packets in order to successfully deliver one data packet from the source to the destination.⁸

5.2 Performances according to node mobility

The performances according to the mobility level are intended to verify the adaptivity and the efficiency of the routing protocol. Figure 8 shows the performances of the routing protocols according to the maximum speed in the RWP mobility model when the number of nodes in the network (N) is 100. In a quite static network with the maximum speed of 5 m/s, AODV is the best in terms of overhead performances and also close or equivalent to the second best protocol, AntHocNet, in terms of the other performances. This is because the flooding operation of AODV is infrequent, resulting in low overhead, but it is sufficient for routing in the static network.

As the mobility increases, the number of disruptions increases rapidly in AODV but slightly in the others. This is because only AODV is the single-path routing protocol. Next to AODV, a large number of disruptions occur in MDSHV because it does not operate additional route maintenance process. AntHocNet and the proposed protocol show a relatively smaller level of disruption and the proposed protocol is better. This implies that the proposed protocol finds more effective alternative paths than AntHocNet to prepare for a future link failure. The number of disruptions directly affects the data delivery ratio; thus, a similar performance aspect is shown. As the mobility increases, AODV shows much worse performance in the data delivery ratio, but the proposed protocol shows the best performance in all mobility ranges.

In terms of the end-to-end packet delay, MDSHV and AntHocNet have a quite longer delay than the other two protocols because they construct multiple paths by the periodic propagation of routing or pheromone information and so this makes it difficult to converge the routing table as the mobility increases. In AODV, as the mobility increases, link failures occur more often and the shortest path is re-established, which has a rather good effect on the end-to-end delay. On the other hand, the proposed protocol shows a gradually decreasing and stationary low delay as the mobility increases because it finds useful alternative paths around the shortest path and adaptively changes the routing path to another one that provides a smaller routing cost according to the topology changes.

The jitter depends on both the end-to-end packet delay and the packet delivery ratio. Thus, the jitter of the proposed

⁸Although two overhead metrics are closely related, the overhead in number of packets is important in measuring the medium access control (MAC) efficiency because it causes MAC layer overhead, and the overhead in number of bytes is important in measuring the channel occupancy and the energy consumption of nodes.

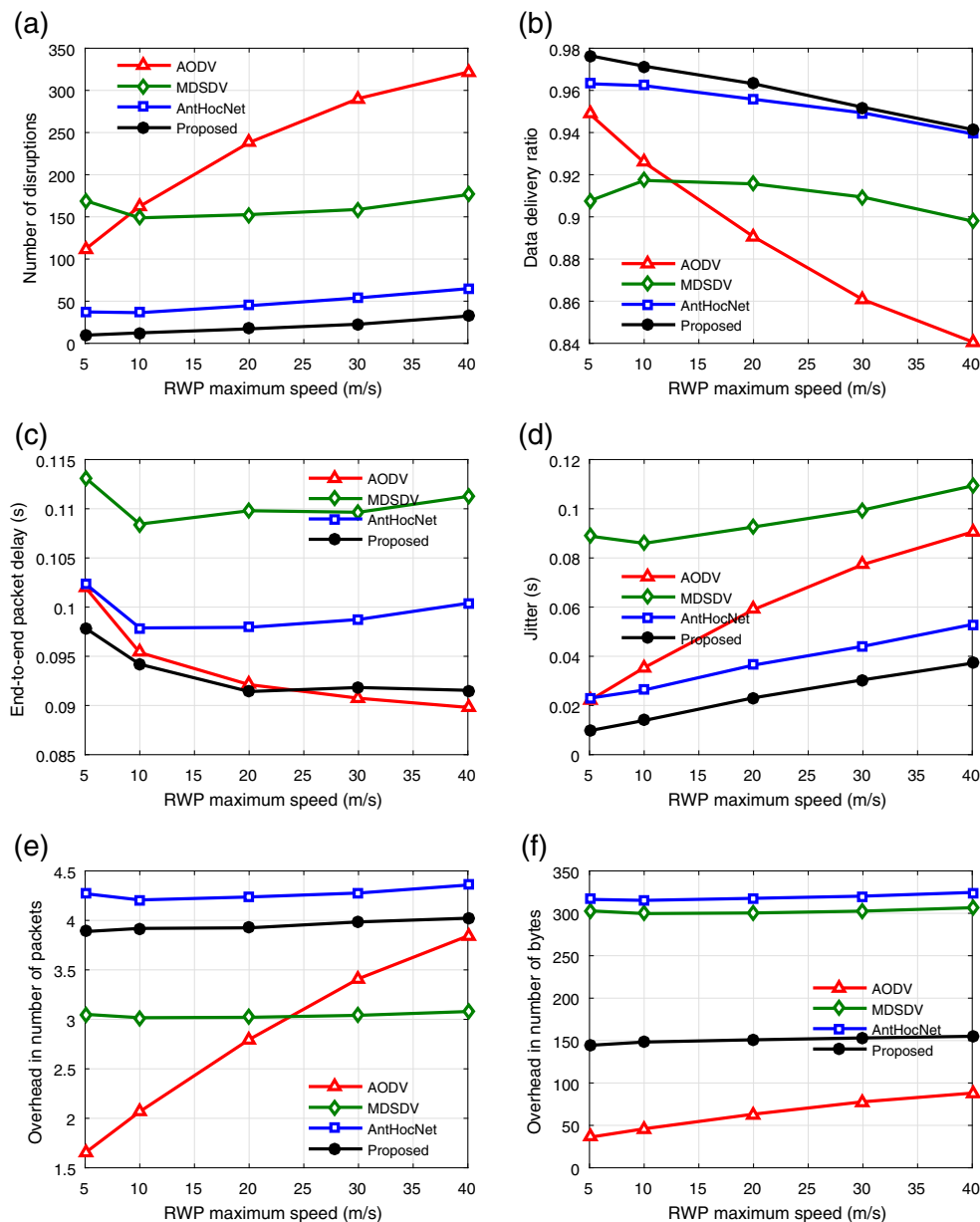


Fig. 8 Performances of routing protocols according to the maximum speed in the RWP mobility model when $N = 100$: **a** number of disruptions, **b** data delivery ratio, **c** end-to-end delay, **d** jitter, **e** overhead in number of packets, and **f** overhead in number of bytes

protocol is a quite better than that of the other protocols because the proposed protocol has a low end-to-end delay and a high data delivery ratio. AODV shows a higher slope than the other protocols because its delivery ratio decreases rapidly as the mobility increases.

In terms of the overhead, AntHocNet has a significantly high overhead irrespective of the mobility level because all the nodes in AntHocNet periodically transmit hello messages for pheromone diffusion and the ant packets are periodically transferred back and forth between the source and the destination for route maintenance. Compared with

AntHocNet, the proposed protocol reduces the overhead because only the one-hop neighbors transmit hello messages for pheromone diffusion. In comparison with MDSDV, the proposed protocol has a higher overhead in terms of the number of packets but a lower overhead in terms of the number of bytes because MDSDV's routing table information, which is periodically transmitted by all the nodes, is fairly large in size. On the other hand, AODV has no periodically generated control packets, and thus, its overhead is very low when the mobility level is low. However, as the mobility increases, its overhead increases linearly because the high

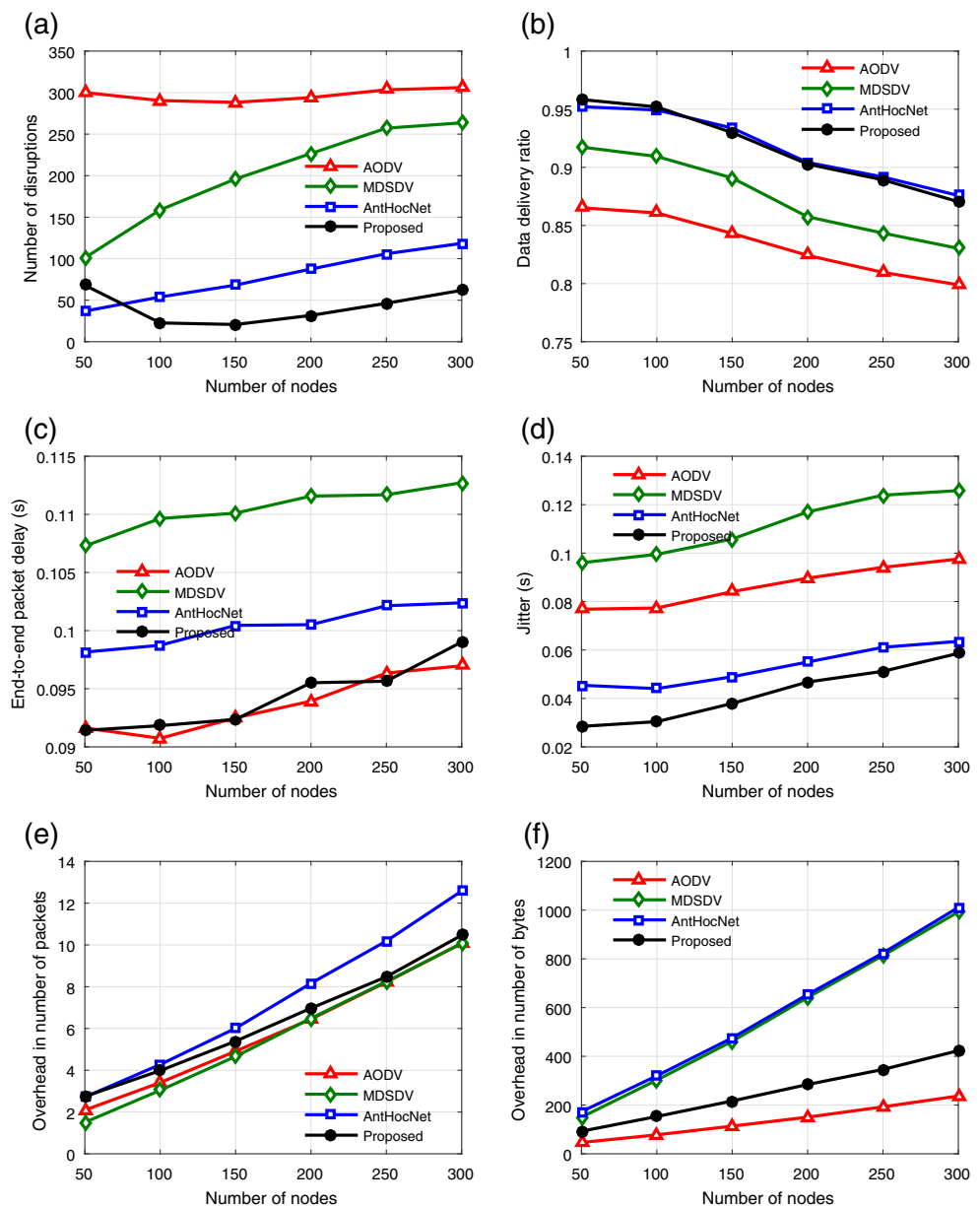
mobility induces more frequent link failures and then generates more route request (RREQ) flooding, which causes a big overhead.

5.3 Performances according to network scale

The performances according to the network scale are intended to verify the scalability of the routing protocol. Figure 9 shows the performances of routing protocols according to the number of nodes in the networks (N) when the maximum speed in the RWP mobility is 30 m/s. As the number of nodes increases, the more control packets are transmitted in the routing protocols, such as AODV, MDSDV and AntHocNet. This increases the probability of

collision for control packets. Moreover, some control packets, such as route request, route reply, and all ant packets, should go through more hops to reach their destination as the network density increases. This causes a longer time for a node to acquire the routing information, and thus, late updating of the routing table. That is, such increased collision and propagation time of control packets make it difficult for each routing protocol to identify the network topology accurately; thus, the number of disruptions and the data delivery ratio deteriorate as the number of nodes increases. The proposed routing protocol is also affected by these two factors so that its performance decreases in the same way as the number of nodes increases. However, such adverse effects on the proposed protocol are weaker than

Fig. 9 Performances of routing protocols according to the number of nodes in network when the maximum speed in the RWP mobility is 30 m/s: **a** number of disruptions, **b** data delivery ratio, **c** end-to-end delay, **d** jitter, **e** overhead in number of packets, and **f** overhead in number of bytes



those on the other protocols because the proposed protocol is required to identify the network topology only within the one-hop region. Therefore, the performance of the proposed protocol is enhanced in terms of the number of disruptions and shows a similar high level in terms of the data delivery ratio.

The end-to-end delay and jitter in all the protocols increase as the number of nodes increases because the average number of transmission hops between the source and the destination increases. It is noted that in this simulation, the communication range of the nodes is set to $2W/\sqrt{N}$ with a fixed value of W , as explained in Section 5.1. Thus, as the number of nodes (N) increases, the communication range of the nodes decreases and this eventually increases the number of transmission hops. MDSDV and AntHocNet show a relatively longer end-to-end delay because their periodic propagation of routing or pheromone information increases the difficulty of identifying the exact topology information as the number of nodes increases. However, the proposed protocol shows a low end-to-end delay that has a similar level as that of AODV and also the lowest jitter because it has both low delay and high data delivery ratio.

As the number of nodes increases, the overheads in terms of the number of packets and the number of bytes increase linearly. The overheads in AntHocNet and MDSDV increase more rapidly because all the nodes in

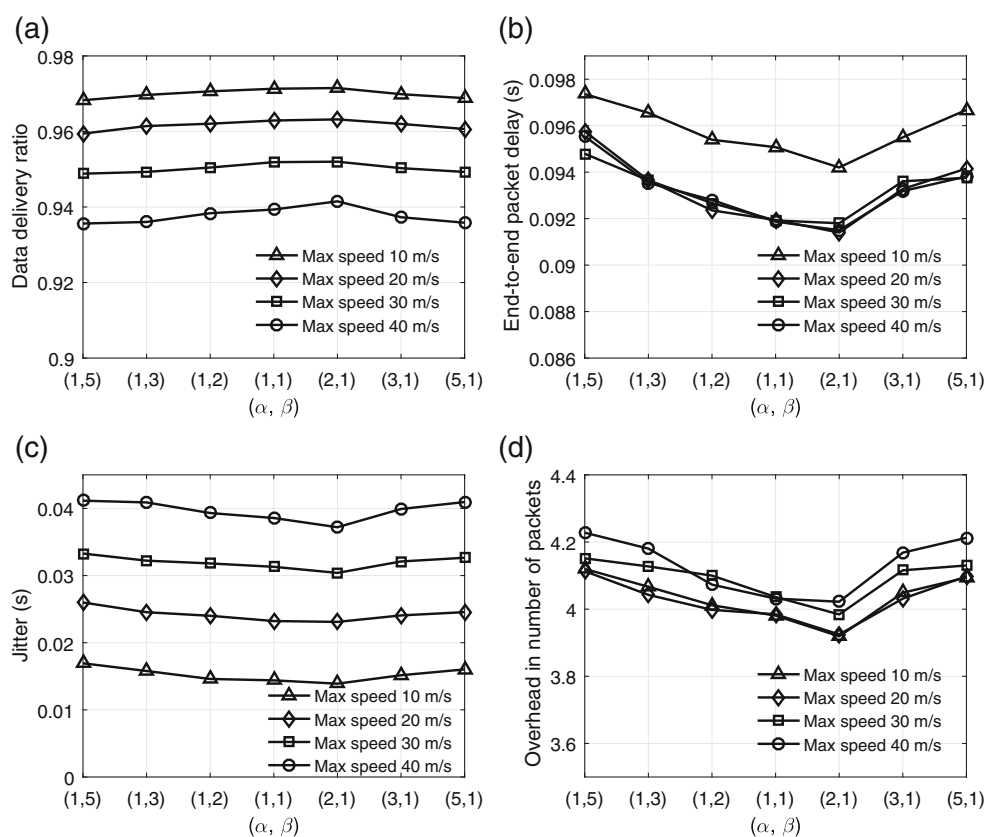
these protocols transmit control packets periodically. Moreover, the overheads in AODV increase as the number of nodes increases because the number of packets transmitted in each RREQ flooding is proportional to the number of nodes in the network. The proposed protocol has a bigger overhead than AODV; however, it shows a more gain in overhead than AntHocNet and MDSDV as the network scale increases.

It is noted that in this study, we do not consider a sparse network with less than 50 nodes in the network. When the network density is very low, our two hypotheses in Section 3 will no longer be established and the performance of the proposed protocol may deteriorate. Therefore in this case, we can use a hybrid approach that selectively employs either the proposed protocol or a low overhead routing protocol, such as AODV, according to the network density.

5.4 Performances according to parameter changes

In this subsection, we investigate the effect of the weighting factors (α , β) and the exploratory parameter (γ) on the routing performances and present suitable values to be used for the proposed routing protocol. Although there are many parameter sets and environment variables to be evaluated, we show main results for parameter determination in the representative environments and consider only four

Fig. 10 Performances of routing protocols according to the change of (α , β)-pair when $\gamma = 5$ and $N = 100$: **a** data delivery ratio, **b** end-to-end delay, **c** jitter, and **d** overhead in number of packets



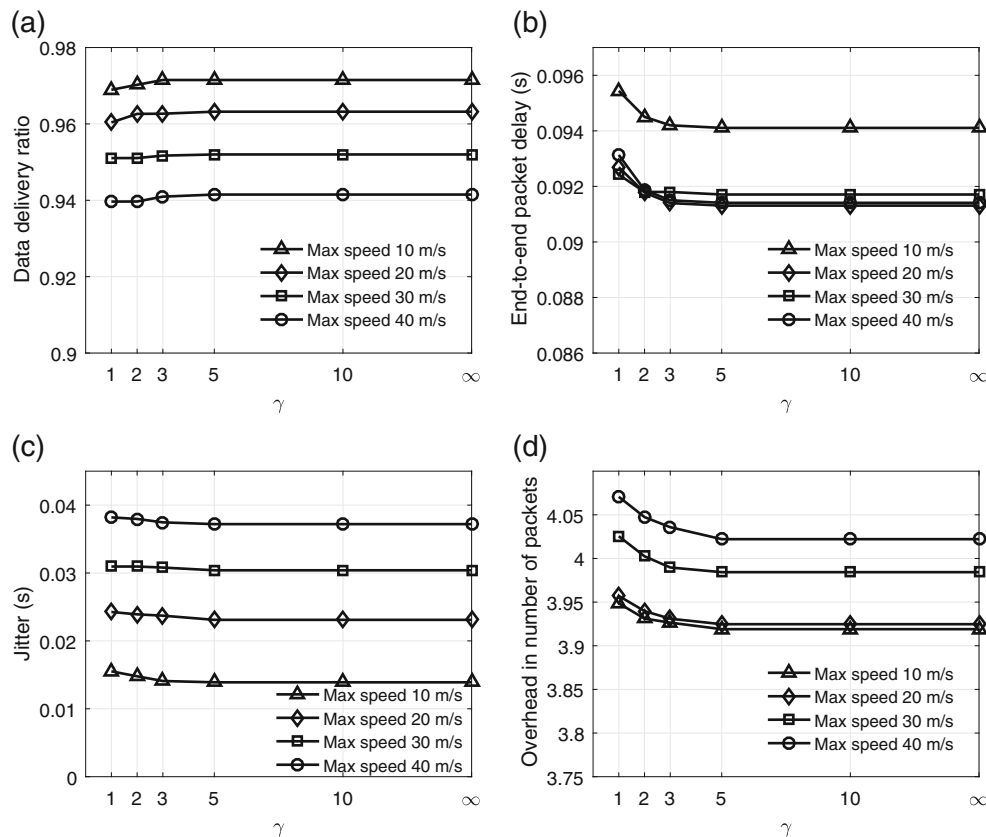


Fig. 11 Performances of routing protocols according to the change of γ when $(\alpha, \beta) = (2, 1)$ and $N = 100$: **a** data delivery ratio, **b** end-to-end delay, **c** jitter, and **d** overhead in number of packets

performance metrics because the number of disruptions and the overhead in number of bytes have a similar tendency to the data delivery ratio and the overhead in number of packets, respectively.

Figure 10 shows the performances of the routing protocols according to the change of (α, β) -pair when $\gamma = 5$, $N = 100$, and the RWP maximum speed varies from 10 to 40 m/s. As shown in Eq. 1, the value of pheromone is inversely proportional to both link cost and elapsed time, in which α weights the link cost and β weights the elapsed time. Therefore, when α is greater than β , the pheromone is affected by the goodness of link rather than the freshness of link, and vice versa. We consider several sets of (α, β) to find the proper ratio of α to β , as shown in Fig. 10. The results show that the performance difference is not significant according to the parameter change, but too high value of α or β degrades performance. Clearly, the overall performance is the best at $(\alpha, \beta) = (2, 1)$. This means that the proposed routing protocol shows better performance when the link cost is more weighted than the elapsed time because the pheromone is periodically updated by ants so that the pheromone evaporation has less impact on the performances.

Figure 11 shows the performances of the routing protocols according to the change of γ when $(\alpha, \beta) = (2, 1)$, $N = 100$, and the RWP maximum speed varies from 10 to 40 m/s. Here, the (α, β) is set based on the previous result in Fig. 10. In Eq. 2, γ determines the amount of exploration that the forward exploration ant is allowed to explore a path toward their destination. When γ is high, the ants are concentrated on the paths with the best pheromone values, so that they limit their exploration to paths that have been indicated to be good by previous ants. On the contrary, when γ is low, the ants can also follow paths with low pheromone. In this way, an alternative path that is better than what their pheromone values indicate (e.g., because of changes in the network or erroneous previous estimates) can be discovered. We vary the value of γ from 1 to 10, and also consider the possibility of deterministically following the best pheromone, which corresponds to a γ value of infinity. As γ increases, the performance is improved and then saturated with constant for all evaluation measures and mobility levels. The reason is that in the proposed route maintenance protocol, the task of exploring new good paths is first performed by the local pheromone diffusion process, which presents the good routes through the indirect

pheromone, and the role of the exploration ants is mainly to determine whether this indirect pheromone information is correct. Hence, when forward exploration ants are requested to do more exploration, the algorithm is less fast to adopt the best routes indicated by pheromone diffusion, and thus, is slower to adapt to new network situations. Therefore, it is beneficial for the proposed routing protocol to set γ greater than 5.

6 Conclusion

Inspired by a pheromone diffusion and rerouting behavior of real ants in nature, we proposed the regional route maintenance protocol for MANETs. In this protocol, pheromones are locally diffused around the shortest path by overhearing the exploitation ants and sharing the overheard pheromone among the one-hop neighbors. Based on this locally diffused pheromone, a probabilistic path exploration is executed by the exploration ants and then useful alternative paths around the shortest path are discovered. To embody these operations, we newly designed two kinds of ants and pheromones. The exploitation ants maintain the shortest path and enable the one-hop neighbors to obtain pheromone information by overhearing, and the exploration ants find useful alternative paths around the shortest path. Moreover, the indirect pheromone formed by the local pheromone diffusion process provides possible routes to reach the destination, and the direct pheromone formed by the regional route maintenance process provides secure routing paths to transmit data. The simulation results showed that the proposed protocol outperforms the conventional routing protocols in terms of the number of disruptions, data delivery ratio, end-to-end delay, and jitter, while effectively reducing the control overhead, according to the node mobility and the network scale. It was also revealed that the regional route maintenance that finds alternative paths around the shortest path is quite effective, especially in high-mobility and large-scale network environments, although it does not search all possible alternative paths throughout the entire network. Therefore, we expect that the proposed regional route maintenance protocol can be effectively applied to highly dynamic and large-scale MANET environments in the future.

By expanding the basic idea of one-hop pheromone diffusion, we can also consider a multi-hop (two or more hops) pheromone diffusion to achieve more reliable routing performance and to operate well in a sparse network. However, this induces more control overhead; thus, there may exist an optimal number of hops for pheromone diffusion suitable to a given MANET environment. We remain this issue for future work.

Acknowledgments This research was supported by Agency for Defense Development (ADD-IBR-245).

Appendix: Demo video for the proposed route maintenance protocol

For the sake of clarity, we provides a demo video for an example operation of the proposed route maintenance protocol. To see our demo video, please visit the following link: <https://youtu.be/hCkjQDK3QFE>.

References

1. Choi H-H, Lee J-R, Roh B, Hoh M, Choi HS (2015) Bio-inspired routing protocol based on pheromone diffusion in mobile ad hoc networks. In: Proceedings of international conference on bio-inspired information and communications technologies (BICT), pp 399–406, New York, US
2. Marina MK, Das SR (2005) Routing in mobile ad hoc networks, Ad Hoc networks technologies and protocols. Springer, Berlin, pp 63–90
3. Perkins CE, Bhagwat P (1994) Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In: SIGCOMM'94, ACM, pp 234–244
4. Clausen T, Jacquet P, Laouiti A, Muhlethaler P, Qayyum A, Viennot L (2001) Optimized link state routing protocol. In: Proceedings of IEEE INMIC
5. Perkins CE (2003) Ad hoc On-Demand Distance Vector (AODV) Routing, IETF RFC 3561
6. Johnson D, Hu Y, Maltz D (2007) The dynamic source routing protocol (DSR) for mobile ad hoc networks for IPv4, IETF RFC 728
7. Dressler F, Akan OB (2010) Bio-inspired networking: from theory to practice. IEEE Commun Mag 48(11):176–183
8. Zhang Z, Long K, Wang J, Dressler F (2014) On swarm intelligence inspired self-organized networking: its bionic mechanisms, designing principles and optimization approaches. IEEE Commun Surv Tutorials 16(1):513–537
9. Bonabeau E, Theraulaz G (2003) Swarm smarts. Sci Am 282(3):72–79
10. Jackson DE, Ratnieks FL (2006) Communication in ants. Curr Biol 16(15):R570–R574
11. Bitam S, Mellouk A, Zeadally S (2015) Bio-Inspired routing algorithms survey for vehicular ad hoc networks. IEEE Commun Surv Tutorials 17(2):843–867
12. Di Caro G, Dorigo M (1998) AntNet: Distributed stigmergetic control for communications networks. J Artif Intell Res 9:317–365
13. Di Caro G, Dorigo M (1998) Two ant colony algorithms for best-effort routing in datagram networks. In: Proceedings of the 10th IASTED international conference on parallel and distributed computing and systems (PDCS'98), pp 541–546
14. Doi S, Yamamura M (2004) An experimental analysis of loop-free algorithms for scale-free networks. In: Proceedings of ANTS, vol. 3172 of lecture notes in computer science, pp 278–285. Springer-Verlag
15. Baran B, Sosa R (2000) A new approach for AntNet routing. In: Proceedings of the 9th international conference on computer communications networks, Las Vegas, USA

16. Carrillo L, Guadall C, Marzo JL, Di Caro G, Ducatelle F, Gambardella LM (2005) Differentiated quality of service scheme based on the use of multi-classes of ant-like mobile agents. In: Proceedings of the ACM conference on emerging network experiment and technology. Toulouse, France
17. Baras JS, Mehta H (2003) A probabilistic emergent routing algorithm for mobile ad hoc networks. In: Proceedings of WiOpt03: modeling and optimization in mobile, Ad Hoc and wireless networks
18. Liu Z, Kwiatkowska M, Constantinou C (2005) A self-organised emergent routing mechanism for mobile ad hoc networks. *Eur Trans Telecommun* 16(5):457–470
19. Marwaha S, Tham CK, Srinivasan D (2002) Mobile agents based routing protocol for mobile ad hoc networks. In: Proceedings of IEEE Globecom
20. Roth M, Wicker S (2005) Swarm intelligence and data mining, chapter termite: A swarm intelligence routing algorithm for mobile wireless ad-hoc networks. Springer, Berlin
21. Rajagopalan S, Shen C-C (2005) ANSI: A unicast routing protocol for mobile ad hoc networks using swarm intelligence. In: Proceedings of international conference on artificial intelligence (ICAI)
22. Zheng X, Guo W, Liu R (2004) An ant-based distributed routing algorithm for ad-hoc networks. In: Proceedings of the international conference on communications, circuits and systems (ICCCAS), pp 412–417
23. Di Caro G, Ducatelle F, Gambardella LM (2005) AntHocNet: an adaptive nature-inspired algorithm for routing in mobile ad hoc networks. *Eur Trans Telecommun* 16(5):443–455
24. Ducatelle F, Di Caro G, Gambardella LM (2005) Using ant agents to combine reactive and proactive strategies for routing in mobile ad hoc networks. *Int J Comp Intel Appl* 5(2):169–184
25. Ducatelle F (2007) Adaptive routing in ad hoc wireless multi-hop networks, Ph.D. Dissertation
26. Lin G, Noubir G, Rajaraman R (2004) Mobility Models for Ad Hoc Network Simulation. In: Proceedings of IEEE Infocom, pp 454–463
27. Ranjan RR (2010) Handbook of mobile Ad Hoc networks for mobility models. Springer Science & Business Media, Berlin
28. Bollobas B, Kozma R, Miklos D (2000) Handbook of large-scale random networks. Springer, Berlin
29. Bettstetter C (2004) On the connectivity of Ad Hoc networks, the computer journal, special issue on mobile and pervasive computing. Oxford University Press 47:432–447
30. Hanzo L, Tafazolli R (2007) A survey of QoS routing solutions for mobile ad hoc networks. *IEEE Commun Surv Tutor* 9(2):50–70
31. Chang X (1999) Network simulations with OPNET. In: The 31st conference on winter simulation: simulation—a bridge to the future-volume 1, ACM, pp 307–314
32. Camp T, Boleng J, Davies V (2002) A survey of mobility models for ad hoc network research. *Wirel Commun Mob Comput* 2(5):483–502
33. King PJB, Etorban AA, Ibrahim IS (2007) A DSDV-based multi-path routing protocol for mobile Ad-Hoc networks. In: Proceedings of PGnet, pp 93–98
34. Jun M (2011) The study on multi-path DSDV in Ad Hoc. In: Proceedings of international conference on communication software and networks (ICCSN). IEEE, pp 299–303