A Performance Comparison of Swarm Intelligence Inspired Routing Algorithms for MANETs

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Abstract. Swarm Intelligence (SI) inspired routing algorithms have become a research focus in recent years due to their self-organizing nature, which is very suitable to the routing problems in Mobile Ad hoc Networks (MANETs). Network topology information can be collected and updated in a distributed and autonomous way via the local interaction among ant-like agents inspired by SI. In this paper we make a comprehensive survey about various SI inspired routing algorithms for MANETs. These algorithms are explained and compared in detail based on a number of network metrics including packet delivery ratio, delay, routing overhead, delay jitter, goodput and throughput etc. It is our hope that the readers can get some hints for their future research work in the realm of SI inspired routing problems from the discussion and simulation results we provide in this paper.

1 Introduction

Mobile Ad-hoc Networks (MANETs) have attracted much attention in recent years due to the rapid advances in Micro-Electro-Mechanical Systems (MEMS). MANETs consist of many mobile nodes (e.g. PDA, notebook) or sensors which can autonomously form a network without relaying on any existing infrastructure. So, they have wide potential applications like battlefield surveillance, disaster rescue missions etc.

In recent years, a new type of Swarm Intelligence (SI) inspired routing paradigm has been becoming a research focus of the routing algorithms for MANETs. Different from the traditional routing protocols [1-3], the SI inspired algorithms [4-12] are self-organized in nature. By adopting the concept of stimergy [13] which means an indirect communication index among different ant agents (software packet), the network information can be collected and updated in a decentralized and dynamic way. Through the localized interaction within various ant agents, global network performance can get optimized, such as energy consumption and load balancing, routing overhead etc.

Our contribution in this paper lies in the following two aspects. First, we present some state-of-the-art SI inspired routing algorithms for MANETs. Second, we give a comprehensive comparison of these algorithms from various network metrics, such as

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packet delivery ratio, delay, routing overhead, delay jitter, goodput and throughput etc. Extensive simulation results are provided with detailed analysis and explanation.

2 Related Work

In MANETs, the routing protocols can be categorized into proactive routing protocols (e.g. DSDV [1]), reactive routing protocols (e.g. DSR [2], AODV [3]) and hybrid routing protocols, which combine both of them. Nevertheless, both proactive and reactive protocols have their intrinsic disadvantages. For example, proactive routing protocols may suffer from heavy communication overhead, especially when the network scale is large or the nodes move very fast. On the other hand, the reactive routing protocols also suffer from longer latency even though they are scalable and effective in reducing the routing overhead.

To tackle the disadvantages above, a variety of Swarm Intelligence (SI) inspired routing algorithms have been proposed with different performance metrics in recent years, as is shown in Table. 1. ABC [4] and AntNet [5] are two of the earliest work about SI based routing for wired networks. The main purpose of ABC is to avoid the traffic congestion and make load balancing in circuit-switched networks by introducing dynamic pheromone updating and aging mechanism. AntNet [5] is a mobile agent based Monte Carlo system with application target of packet-switched networks. [6] provides a survey and some new directions about Ant Colony Optimization (ACO) based routing for wired network.

ARA [7] is the first routing algorithm for MANETs which is based on the concept of SI and especially on ant colony based meta heuristic. In ARA, the routing table is maintained through data packets so as to reduce routing overhead. The uniqueness of PERA [8] is that the probability to select next hop is uniformly distributed during certain percent of time rather than pheromone based. Same as the authors in[5], the authors of AntHocNet [9] extended their rich experience of wired network routing to the MANETs routing problems. It is a hybrid routing algorithms which combines the reactive route setup phase and proactive route maintenance phase together. Similar to [9], the authors in [10] are the same as [11] whose application target is the fixed network, and their latest work can be found in [14]. Finally, in [12], the SI inspired routing algorithm is for the first time applied to hybrid ad hoc networks which include

Table 1. Various SI inspired routing algorithms and main metrics

Algorithm Name	Packet delivery ratio	Delay	Routing Overhead	Delay Jitter	Good put	Through-put
ABC(96)	YES					
AntNet(98)		YES	YES			YES
ARA(02)	YES		YES			
PERA(03)	YES	YES			YES	YES
AntHocNet(04)	YES	YES	YES	YES		
BeeAdHoc(05)	YES	YES	YES			
ANSI (06)	YES	YES	YES	YES	YES	YES

both pure MANETs and other highly capable networks, such as mesh networks or cellular networks. So, the routing strategy can either be proactive or reactive which depends on whether it is connected to a highly capable network or not.

3 Swarm Intelligence Inspired Routing Algorithms in MANETs

In order to understand the characteristics of Swarm Intelligence, we will first look at the SI inspired routing problem in MANETs with an example. Then, we will explain the self-organizing nature of SI in the context of routing for MANETs.

3.1 Swarm Intelligence Inspired Routing Procedure

3.1.1 Route Setup Phase

As is shown in Fig. 1, each node has a routing table as well as a pheromone table. Once node 1 has packets to send, it will first check its routing table in Table 2. The row in routing table represents its neighbors and column represents the destination node. If there is no information about the destination node 5, it will then initiate the route setup phase. Then, it will broadcast a route request packet (ant agent) to its neighbors to find information of node 5. If the neighbor node does not have the information about destination, it will once again broadcast until it finally reaches the destination. During this process, the intermediate nodes are saved in the request packets in a sequence order like P= {1, 2, 5}, and a sequence number is adopted so as to avoid the loop. Once the request packet reaches node 5, a route reply packet will be sent on the reverse route of P. It is worth noting that the route information and pheromone information is not updated until the backward process so as to reflect the latest network situation. Then, the hop number and time stamp from destination node 5 to each of the intermediate node are recorded in their routing table and pheromone table based on heuristic function. The entry in the routing table can be a combination of

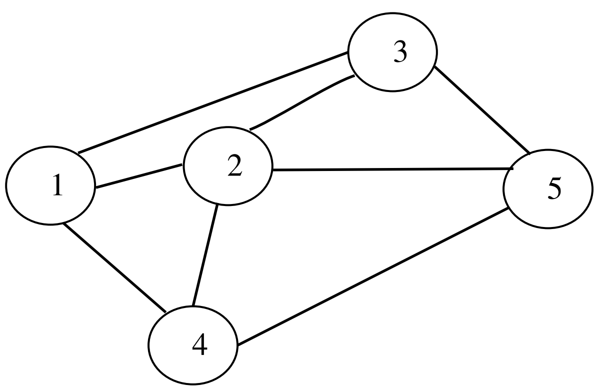


Fig. 1. Illustration of SI based routing problem

Table 2. Routing table of node 1

	2	3	4	5
2	$p_{2,2}$	$p_{2,3}$	$p_{2,4}$	$p_{2,5}$
3	$p_{3,2}$	$p_{3,3}$	$p_{3,4}$	$p_{3,5}$
4	$p_{4,2}$	$p_{4,3}$	$p_{4,4}$	$p_{4,5}$
5	$p_{5,2}$	$p_{5,3}$	$p_{5,4}$	$p_{5,5}$

both delay and hop number, so that those with a shorter delay and hop number can be selected as next hop to the destination later on. Finally, the route will be established and the data packets can be sent from node 1 to node 5.

3.1.2 Route Maintenance Phase

It is worth mentioning that during the route setup phase, multiple path could be built based on the broadcasting mechanism, like another path P' = {1, 3, 5} etc. So, the selection of next hop can be based on the pheromone table, whose entry $p_{i,j}$ is a probability which is calculated as follows [13]:

$$p_{i,j} = \frac{(\tau_{i,j})^{\alpha} \cdot (\eta_{i,j})^{\beta}}{\sum_{k \in N_i} (\tau_{k,j})^{\alpha} \cdot (\eta_{k,j})^{\beta}} \tag{1}$$

Here, $\tau_{i,j}$ is pheromone value and $\eta_{i,j}$ is an index of link quality which can be simply represented as $1/d_{i,j}$. N_i is the neighbor number of node i (here is the source node 1). α and β are two tunable parameters which control the convergence of algorithm. The neighbor with a higher probability will have more chance of being selected as next hop. From Eq. (1), we can see that nodes with a shorter distance to their previous node or with a higher pheromone value are more likely to be chosen as next hop. Suppose the pheromone value in node 2 and 3 are the same, then node 2 will have a higher probability to be chosen as the next hop since its distance to node 1 is shorter than node 3.

The route information can be maintained through periodical "hello" packets or even the data packets [7]. Since the selection of next hop is probability based, the work load on one route can be shared by the other route to make load-balancing.

3.1.3 Route Failure Handling Phase

Due to the dynamic nature of MANETs, once there is a link failure because of node movement or out of energy, the following measures can be taken. Supposing node 2 has moved out of the range of node 1 and link fails between node 1 and node 2. First, node 1 will set related routing table and pheromone table entries of node 2 as empty. Then, it will check its routing table again to find an alternative route. Here, there are two other candidates, which are {1, 3, 5} and {1, 4, 5}. So, node 1 will choose the one with a larger $p_{i,j}$. If there is no alternative route, the route setup phase will be initiated again.

3.2 Self-organizing Nature of Swarm Intelligence

Here, we will introduce the self-organizing nature of Swarm Intelligence in the context of routing for MANETs. The main ingredients of SI lie in the following four aspects, which are positive feedback, negative feedback, amplification of fluctuations and multiple interactions among multi-agents [13].

3.2.1 Positive Feedback

The notion of positive feedback is also tightly related with reinforcement learning, which is a branch research of Machine Learning in the field Artificial Intelligence. Once certain link is visited again, the pheromone value along that link is incremented by a small constant amount. Later on, that link will have a higher probability of being revisited based on formula (1). This is because it demonstrates a better link performance, such as shorter distance, lowers latency or higher remaining energy etc. However, traffic congestion and link failure are likely to be caused if the pheromone value is monotonously increased. So, the negative feedback and certain thresholding mechanism need to be adopted simultaneously.

3.2.2 Negative Feedback

Similar to the evaporation of pheromone, once certain links are not visited for certain time, it shows that those links might have a lower priority in the aspects of energy-efficiency or end-to-end delay etc. So, the pheromone along those links needs to be decreased by a certain amount. Both linear and non-linear decreasing functions can be adopted here based on the application scenarios. The decreasing function needs to be carefully selected because a faster decreasing mechanism will deteriorate the goodness of certain node with higher priority while a slower decreasing mechanism will hinder the convergence of network performance.

3.2.3 Amplification of Fluctuations

This is a critical factor in many self-organizing systems. Without it, most of the self-organized systems will turn back to static and deterministic systems rather than dynamic and stochastic systems. It provides more candidate solutions with lower priority, which might seem to be inferior at first. For example, node 4 might seem to be inferior at first. But it still has a probability of being chosen as the next hop of node 1 and the pheromone value will be added. Later on, node 2 might become more suitable to share the work load with node 2. In that case, a load-balancing can be made so as to avoid node 2 from ding out of energy quickly.

3.2.4 Multiple Interactions

This is also one of the critical factors to ensure the system robustness. As we mentioned before, during the route failure phase, other alternative routes can be chosen based on the multiple interaction among ant-like agent packets. Besides, during the process of route setup phase, even though one of the ant agents fails, a route can still be found by other ant agents. In the mean time, the convergence rate can also be accelerated by this parallel route searching mechanism.

4 Performance Evaluation

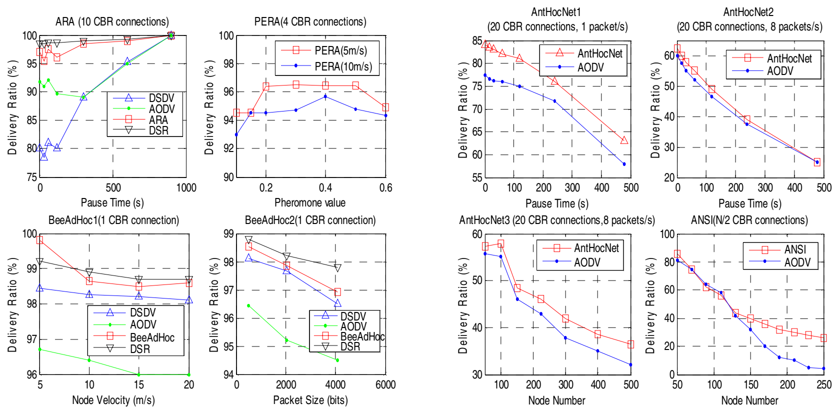
From Table 1 and Table 3 we found that two major problems exist in the simulation of various SI inspired routing algorithms. First, different network metrics are used for performance evaluation. They are defined and compared based on different criteria. Second, the network environment which includes network size, node number, mobility model and traffic model etc. is different between them. So, we try to compare all of there performances and draw some common conclusion in this survey paper. Later on, we can deepen our future study based on the analysis and comparison here.

4.1 Simulation Environment

In the simulation environment, N number of nodes are randomly deployed in a [X, Y] m^2 area with a maximum transmission radius of R meters. The most commonly used mobility model is called “random waypoint (RWP)” model, among which a node will move with a certain velocity uniformly distributed in the range of $[V_{min}, V_{max}]$. Here V_{min} is usually set as 0 and V_{max} is the maximum velocity. After reaching one place, the node will stay there for a certain pause time and then randomly move to the next place with a new velocity. A total simulation time is set so that it will finally converge no matter the traffic session is finished or not. A constant bit rate (CBR) traffic model is adopted, and K number of connections can be selected randomly from N nodes as source and destination pairs. The packet rate can be set as 1, 4, 8 or 16 packet(s)/s and the packet size is usually defined from 64 bytes to 1024 bytes. The traffic can be initiated and terminated at any time within the simulation time.

Table 3. Simulation environment comparison

Algorithm	[X,Y] (m^2)	N	R (m)	Vmax (m/s)	Pause Time (s)	Simulation Time (s)	Conn. Num.	Packet Size (Byte)	Packet Rate (p/s)
ARA	1500 *300	50	250	10	0, 30… 120,300	900	10	64.. 1024	4
PERA	500 *500	20	250	20	50, 100	900	4	*	1
Ant HocNet1	3000 *1000	100	300	20	0..480	900	20	64	1
Ant HocNet2	1000 *1000	100	110	20	0..480	900	20	64	8
Ant HocNet3	[750^2] [2250^2]	50.. 500	110	20	30	900	20	64	8
BeeAdHoc	2400 *800	50	250	1..20	60	1000	1	64	10
ANSI	[1100^2] [2460^2]	50.. 250	250	20	10	300	N/2	64	1



(a) (b)

Fig. 2. Packet delivery ratio comparison

4.2 Simulation Results and Comparison

Here, we do not compare ABC and AntNet with other routing algorithms since they are wired network oriented. It should be noted that in Table 3, the AntHocNet algorithm can be further classified into three types based on its application scenario. AntHocNet1 is dealing with light traffic since 20 CBR traffic pairs send out 1 packet per second. AntNetHoc2 is dealing with heavy traffic with packet rate of 8 packets per second. AntHocNet3 is similar to AntHocNet2 except that the node density is kept as a constant (1 node per 100×100 m^2). Besides, there are five experiments in ANSI, ranging from hybrid network with UDP, hybrid network with TCP, large hybrid network with UDP to pure MANET with TCP and pure MANET with UDP. Here, we choose the last experiment, namely pure MANET with UDP, since our network environment is pure MANET with UDP BCR traffic.

4.2.1 Packet Delivery Ratio

Packet delivery ratio means the ratio of correctly delivered packets versus the total packets sent. From Table 1 we can see that it is one of the most commonly compared network metrics by most SI inspired routing algorithms.

From Fig. 2 (a) we can see that packet delivery ratio increases with pause time in ARA. Here, the performance of DSR is the best and ARA is a little inferior to DSR. But their performance is both above 95%. However, in Fig. 2 (b), this performance of AntHocNet decreases with pause time under both light and heavy traffic. The reason is that the network topology is sparse and there are some isolated nodes with no neighboring nodes. So the nodes may not successfully forward the packets to other nodes. The PERA algorithm shows that the packet delivery ratio is higher with lower node velocity, and the difference is not so much. BeeAdHoc algorithm once again verifies the conclusion of PERA, which is that the packet delivery ratio decreases with high node velocity. In BeeAdHoc2, we can see that larger packets can cause

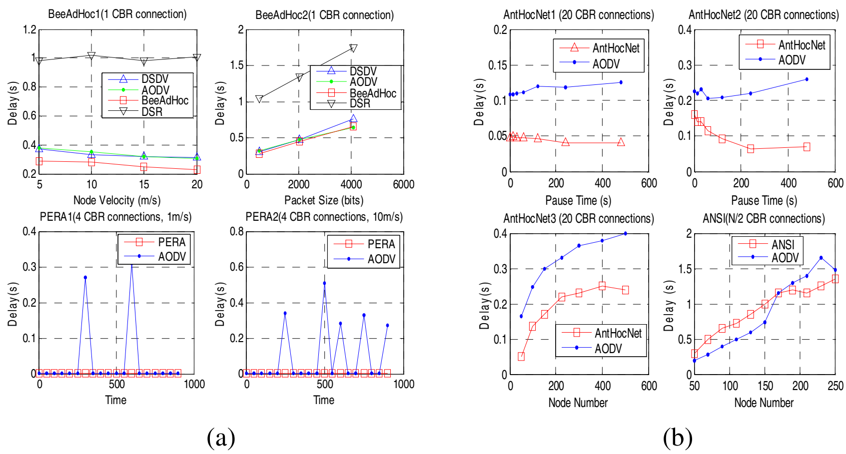


Fig. 3. Delay comparison

traffic congestion and thus decrease the delivery ratio. Once again, DSR has the best performance as is shown in ARA algorithm. So, we can still draw some common conclusions through the comparison here. Finally, for the relationship between packet delivery ratio and node number, we see from both AntHocNet3 and ANSI that it decreases with node number. It shows that both of these two SI inspired algorithms scale better than AODV, especially when the node number is above 150.

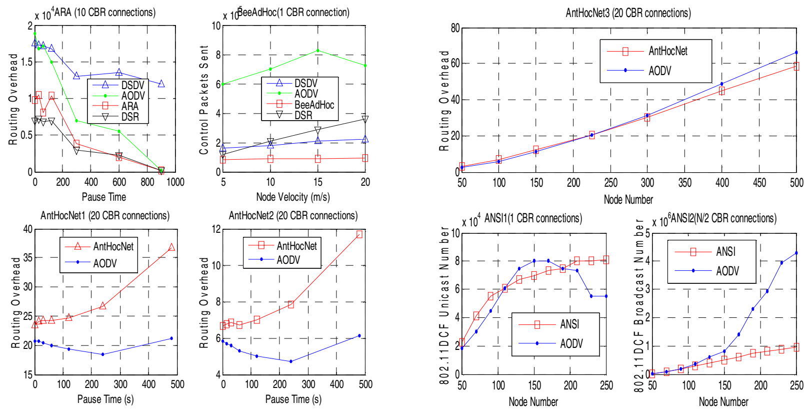
4.2.2 Delay

From Fig. 3 (a) we can see that node velocity has no influence on end-to-end delay in BeeAdHoc algorithm. Even though DSR has the best performance of packet delivery ratio, here it has the worst performance of delay. Due to the simple data structure and less control packets used in BeeAdHoc, it has a good performance of delay. The influence of packet size lies in that it can cause traffic congestion and delay the packet transmission. For PERA algorithm, we can once again draw a common conclusion that velocity has little impact on delay. However, there is a sharp increase in AODV during certain time on both low and high velocity cases. The reason is that AODV needs more time to deal with traffic congestion or link failure, while in PERA, the data packet can be transmitted through an alternative path as we mentioned before.

In Fig. 3 (b), the delay of AntHocNet is about one third or half of AODV at light traffic. For heavy traffic situation, the trend is still the same. The reason is that AntHocNet is a hybrid routing algorithm with proactive route maintenance function. Same conclusion can be drawn from the simulation results of AntHocNet and ANSI that delay increases with node number. Since the node density is kept constant in both algorithms, the network size also increases with node number. For a larger number of nodes, more nodes are involved into the traffic session, which will usually cause more hop number and delay.

4.2.3 Routing Overhead

Routing overhead is defined as the average number of control packet transmissions per data packet delivered in AntHocNet algorithm, while it is usually defined as the



(a) (b)

Fig. 4. Routing overhead comparison

specific number of routing packets sent in other algorithms. From Fig. 4 (a), we can see a general trend which is that more routing overhead is needed with higher mobility. Specifically speaking, when a node stays in certain position for a longer time, the less control packets are needed in ARA. We may recall that in BeeAdHoc, foragers are only sent back when the destination has packets to send to the source node and it is put in the header of the beeswarms. In that case, less control packets are needed, causing a large decrease of routing overhead. In AntHocNet however, the routing overhead is a disadvantageous factor. Actually, it pays for all the other advantageous factors in AntHocNet, such as delivery ratio, delay and delay jitter. In contrast with ARA, it uses more control packets to discover and maintain the route. The longer one node stays, more packets will be sent there.

It is also worth noting from Fig. 4 (b) that AntHocNet algorithm can also gain advantage over AODV when the network scale is large. It seems route maintenance and route failure handling mechanism play a trade-off. Again, half number of nodes' involvement as data sources may cause traffic congestion, thus increase the controlling unicast or broadcast packets in ANSI.

4.2.4 Delay Jitter

As an important metric of QoS, delay jitter means the average difference in inter-arrival time between packets. The performance of AntHocNet is always better than AODV from the observation of Fig. 5. For AntHocNet, the average delay jitter is smaller on heavy traffic than on light traffic based on its definition. If nodes move more frequently, delay jitter will also be small as we can imagine. Even if the node number increases to 300, this performance of AntHocNet is still very good in comparison with AODV. On the other hand, traffic congestion might be easily caused in ANSI since half of the nodes are serving as data sources. Due to the slow packet rate and large network size, which is corresponding to the node number, the delay jitter in ANSI is relatively larger than that in AntHocNet.

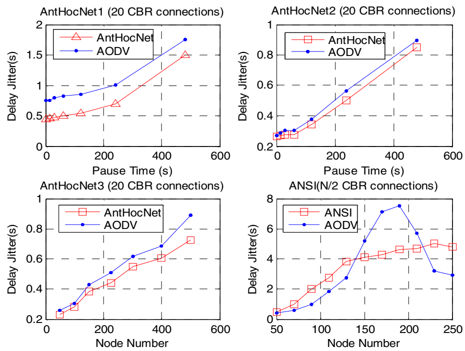


Fig. 5. Delay jitter comparison

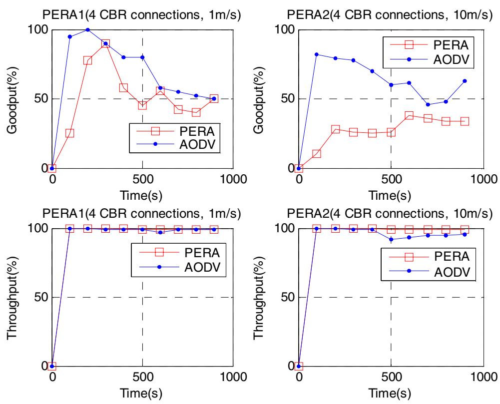


Fig. 6. Goodput and throughput comparison

4.2.5 Goodput and Throughput

From Fig. 6 we can see that the goodput of PERA is inferior to AODV on both low and high velocity occasions, and it decreases with high mobility. This is because more control packets are sent out so as to find new paths when certain link is broken due to the fast movement of nodes. The performance of throughput is nearly the same for AODV and PERA under different mobility.

5 Conclusion and Future Work

In this paper, we make a comprehensive comparison and analysis of SI inspired routing algorithms for MANETs. The self-organizing nature of SI and the integration of SI principle with routing mechanism are illustrated and explained. It is our hope that the readers can get some hints for their future research work in the realm of SI inspired routing problems from the common conclusions we draw as well as our comparative figures and tables.

In the near future, we will study the energy consumption and load-balancing performance of the SI inspired routing algorithms. Besides, the heuristic functions to associate pheromone with probability and other network metrics, such as delay, hop number and remaining energy will also be studied.

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