Routing selection in mobile ad hoc network using soft computing approaches

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Abstract: Routing in the mobile ad hoc network (MANET) is a challenging task and has received a great amount of attention from researchers. This paper introduces an exact reference routing model to find the shortest path (optimum route). This model is a conventional combinatorial that selects the shortest route from all possible routes. To demonstrate the use of this reference model for comparison a second model is selected which is a modified ant colony optimisation (ACO). The good selection of the heuristic parameters of the ACO model increases its matching degree with the reference one. Therefore, a training pre-processing phase is added to select the best parameters for ACO model. The two models are compared using four different criteria. These criteria are the execution time, energy consumption, the total cost, and the network lifetime. A simulation experiment is performed, and the results show that the modified ant colony algorithm is superior in execution time but consumed more energy than the reference combinatorial and its total cost is greater than or equal to the other one. The lifetime analysis shows that the reference model has better lifetime than the modified ACO model.

Keywords: routing; mobile ad hoc network; MANET; ant colony; energy consumption; execution time; total cost; shortest path; optimum route; simulation.

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1 Introduction

Mobile ad hoc networks are wireless networks without any infrastructures such as access points or base stations in which nodes forward packets for each other, allowing nodes beyond direct wireless transmission range of each other to communicate over possibly multi hop routes through a number of intermediate nodes (Kushwaha and Mishra, 2016).

An ad hoc network is self-organising and adaptive. This means that a formed network can take different forms (topologies) without the need for any system administration. The term ‘ad hoc’ tends to imply ‘can take different forms’ and ‘can be mobile, standalone, or networked’. A mobile ad hoc network is commonly referred to as MANET. MANET is a network that consists of wireless mobile nodes such as PDAs, laptop computers, and smart phones (Kushwaha and Mishra, 2016). MANET is used in various applications including sensor networks and rescue and guidance systems in disaster situations (Menon et al., 2016). The mobility of the nodes and limited capacity (bandwidth) of the wireless channel, limited power sources together with wireless transmission effects such as attenuation, and interference, are combined to create significant challenges for network routing protocols operating in an ad hoc network. In ad hoc network, a distributed routing protocol is employed to determine the hop-by-hop path that a packet follows between source and destination. The main purpose of routing is to bring packets efficiently to their destination. Most of the current research in MANETs is on efficient and scalable routing algorithms. The mobility of network nodes, the variability of wireless link quality and the lack of hierarchical structure in the physical topology of the network makes routing in MANETs much more difficult than in wired networks.

The research problem can be stated as follows. There are several algorithms that address routing problem. Each author of an algorithm claims that his algorithm is better than others using simulation with different metrics. The main problem is that there is no a concise reference that can be used to measure the exactness of the proposed algorithm. Also, there is no agreement of the quality of service metrics.

The main purpose of this paper is to introduce a new exact reference model to find the shortest path (optimum route) from point of view of the exactness of the solution. Unfortunately this reference model is suffering from the huge execution time problem.

The second purpose of this paper is to demonstrate the use of this reference model to compare other routing algorithms such as Dhurandher et al. (2009), Misra et al. (2009, 2010a, 2010b, 2010c), Misra and Rajesh (2011) and Oommen and Misra (2010).

Instead of using an already published algorithm, the paper modified the most famous routing algorithm which is the ant colony optimisation (ACO) algorithm using a pre-processing phase (training phase for parameter selection). A comparison study is performed using simulation based on an identical network topology and same requests and also same quality of service criteria are applied to obtain the final results.

Soft computing is the use of inexact solutions to computationally hard tasks such as the solution of NP-complete problems, for which there is no known algorithm that can compute an exact solution in polynomial time. The principal constituents of soft computing are fuzzy logic, neural computing and evolutionary computation, machine learning. ACO is one of the most commonly used evolutionary algorithms in MANET.

In this paper, two routing algorithms for MANET are introduced. The first one is a conventional combinatorial that selects the shortest route from all possible routes using the maximum number of hops as a constraint. This algorithm will be used as a bench mark (reference model). The second is a special version of ACO. The two algorithms are compared using different performance evaluation criteria by the means of simulation experiments (Papadopoulos et al., 2016). These criteria are the execution time, the energy consumption, the total cost and the number of dead nodes.

The paper organisation is as follows: Section two gives an overview of the related work of MANET routing algorithms and discusses its shortcomings. Section three describes the proposed models (combinatorial routing and the special version ACO routing algorithms), and section four explains the simulation experiment set up and shows the results of the comparative study. Then the paper is ended by conclusions in section five.

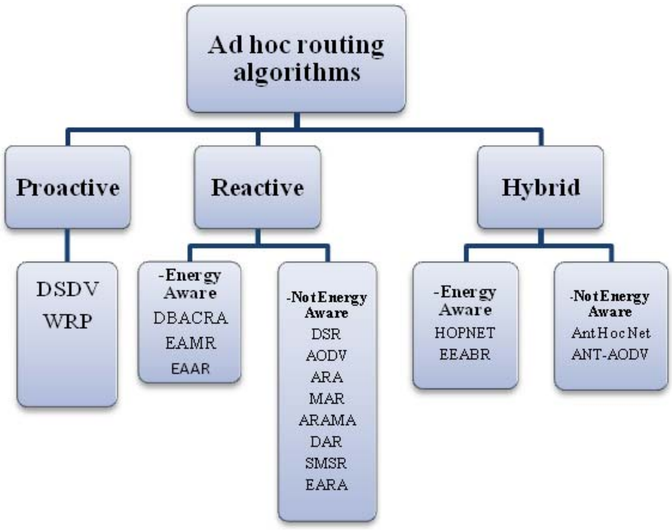
2 Related work

There are three main classes of routing protocols:

1. proactive technique which is continuously updating the reachability information (in routing tables) in the network and when a route is needed, it is immediately available
2. reactive technique in which the routing discovery is initiated only when a request for packet transmission is needed
3. hybrid technique which combined both of them.

The routing protocols categorisation can be shown in Figure 1.

Figure 1 Routing protocols categorisation (see online version for colours)



2.1 *Proactive routing protocols*

- DSDV: destination sequenced distance vector

  This protocol has to update continuously the routing tables. This process tends to waste network resources just for maintaining large amounts of routing table data (Mummadisetty et al., 2015).

  It can be a serious problem because the network resources in MANET are limited and assumed not to be stable. Too much internal activity may limit the ability to transmit communication data packets for the actual users.

- WRP: the wireless routing protocol

  It is a table-based distance-vector routing protocol. Each node in the network maintains a distance table, a routing table, a link-cost table and a message retransmission list (Manoj and Chandras, 2012).

  This protocol is also suffering from too much overhead like other proactive protocols.

2.2 *Reactive routing protocols (not energy aware)*

- DSR: dynamic source routing

  This protocol may produce unacceptable delays in forming the forward route. In the basic version of DSR, every packet contains the entire route in the header of the packet (Jagannadha et al., 2012).

  DSR includes source routes in packet headers and large headers can reduce performance, particularly when data contents of a packet are small.

- AODV: ad hoc on-demand distance-vector

  This protocol tries to improve on DSR by maintaining routing tables at the nodes, so that data packets do not have to include routes. AODV retains the necessary feature of DSR that routes are updated only between nodes which need to communicate (Shrivastava et al., 2013).

- ARA: ant colony-based routing algorithm

  It is a purely reactive MANET routing algorithm. One of its important characteristics is that it does not use the hello packet to explicitly find its neighbours (Kumar and Prasad, 2015). The main objective of ARA algorithm is the decrease of route overhead (Rajan et al., 2015). In ARA, the pheromone values are calculated by the number of hops, and delay time is not considered.

- MAR: mobile agent routing

  In MAR, each data packet is considered as an agent that discovers the network to gather routing information. The ant agent of MAR has a history list with fixed length. The list contains the intermediate nodes the ant agent has visited (Zhou and Heywood, 2004)

- ARAMA: ant routing algorithm for mobile ad hoc networks

  In ARAMA the pheromone is updated according to the path grade of the ant. The path information of the forward ant (such as hops, remaining energy, bandwidth, and queue length) is recorded. The formula of the grade relies on the link information such as energy (Kaur, 2015).

- DAR: distributed ant routing protocol

  In the DAR protocol, the forward ants only care about the nodes in crosses and select next hop by only using the pheromone information. The backward ants only release a constant value of flavour in the coming back link. Nodes stochastically select the next hop according to the pheromone when it sends data packets. In the DAR protocol, ants record all the passed nodes' IDs, so it is suitable for small networks (Rosati et al., 2008). The network's convergence is slow and sometimes also leads to local optimum.

- SMSR: shortest multiple routing algorithm

  The number of routes is formed between given pair of source and destination. RREQ whose RREP arrives first at source becomes the shortest path. The shortest of these routes is primary route. It is used essentially for data transfer. Next two shorter paths are secondary routes (Kulhalli and Rane, 2014).

- EARA: enhanced ant colony-based routing algorithm

  In EARA, the initial pheromone value is set by not only the total number of hops made by the forward ant, but also by the time interval between the sending of the forward ant and receiving the backward ant (Arif and Rani, 2011). This difference creates a better delivery ratio.

2.3 Reactive routing protocols (energy aware)

- EAMR: energy-efficient ACO-based multipath routing algorithm

  EAMR has upgrading and innovation in pheromone update formulas, pheromone update mode. It considers factors like rate of energy consumption and end-to-end delay (Tong et al., 2015).

- DBACRA: diffusion-based ant colony routing algorithm

  The protocol is divided into two types, the actual and virtual pheromones, which guide the ant packet and data packet to the path search, when the actual pheromones of the backward ants are from the destination node, releasing the link of the pheromone (Rong et al., 2011).

- EAAR: energy-aware ant-based routing protocol

  It is an ACO-based multi-path routing protocol; it takes into consideration the several factors such as the power consumed in transmitting a packet and the residual battery capacity of a node to increase the battery life of the nodes by decreasing the repetitive use of a selection of these nodes (Misra et al., 2010a).

2.4 Hybrid routing algorithm (energy aware):

- HOPNET: hybrid ant colony optimisation routing algorithm for mobile ad hoc network protocol

  This protocol divides the network into a plurality of areas and adopts proactive routing in areas and reactive routing between areas. The cost of internal proactive routing is not great (Wang et al., 2009). HOPNET has more benefits in large networks.

- EEABR: energy-efficient ACO-based routing protocol

  The forward ant's head of the EEABR protocol can record nodes' IDs with the two recent hops which decrease the length of the forward ant packet, save the energy consumption of nodes, and prolong the life of wireless sensor networks. But the EEABR uses the same packet structure of the forward ant and the backward ant which increases the unnecessary energy cost (Abazeed et al., 2014). EEABR regularly sends forward ants in proactive routing mode.

2.5 Hybrid routing algorithm (not energy aware)

- AntHocNet: it is an ACO-based multipath hybrid routing protocol

  The protocol is reactive in route discovery and proactive in route maintenance. The routing algorithm has four major parts: reactive route forming, data transmission, proactive route maintenance, and link failure handling. When a node which does not have route information to the destination node needs to communicate, it broadcasts a forward ant with all its neighbours for route discovery. Each node has a pheromone table. If the table has pheromone information to the destination node, the forward ant selects the next hop based on pheromone information in the tables. In addition, each node holds a routing table which contains all the destination nodes that the node can reach (Houssein and Ismaeel, 2015). It is not suitable for large-scale networks.

- Ant-AODV hybrid routing protocol

  The base protocol is an on-demand type (AODV). When the source node does not have the route information to the destination, it starts route discovery procedure. It provides, however, a proactive mode to update the routing tables of participating nodes so that they decrease the frequency of the on-demand route discoveries (Glabbeek et al., 2016).

In this section we have reviewed different routing algorithms used in MANET. Any routing algorithm used in MANET share common shortcomings. The methods based on the reactive routing have to wait until the communication routes from the source to the destination have been established (Cauvery and Viswanatha, 2008). For example, DSR and AODV, like the ACO approaches, take some time to discover the route, which delays the establishment of the connections in a large-scale network (Shrivastava et al., 2013).

On the other hand, with the methods based on the proactive routing algorithms, since the route from a source node to the destination may have been already found, the source node can transmit data packets without the delay. The methods based on the proactive approach, however, may not function well because the network topology of a MANET is dynamic and lives of the routes are rather short (Deepalakshmi and Radhakrishnan, 2009). They also have too much overhead for relatively the small bandwidth used in MANET. In order to solve the problem of the overhead of backward ants, (Girme, 2015) has proposed a routing algorithm that uses only forward ants to update the routing table of intermediate nodes. The forward ants of this algorithm keep the path length from the source node, and update the routing table based on the information. The pheromone value at each intermediate node is given by the forward ant that comes through the shortest path from the source node. Whenever a node needs to send data packets to the source node, it can use the shortest path for the connection. Ants utilise the routing tables as shared data structures by which they exchange information with each other. Routing tables are maintained by the ants only for exchanging routing information between each other. Therefore forming a communication route from the source node to the destination node before transmitting data packet is not necessary and it is natural not to use backward ants to maintain routing tables to obtain the best route. This paper tries to consider most of the previous issues in Section 3.2 dealing with the modified ACO algorithm.

3 Proposed models

3.1 Conventional combinatorial model

This approach is based upon selecting all possible routes. From these routes the shortest one is selected. The good thing about this model is the result which is the exact shortest path. It can be used as a reference for comparison with other approaches. Although the shortest path is not the only objective but it is one of the important issues since shortest path can guarantee less energy consumption and less total cost. The algorithm is based on the combination and permutation mathematical function.

The algorithm steps are given as follows:

Algorithm 1 Conventional combinatorial algorithm

Step 0	Topology design: • Select the number of nodes (*n*) and the terrain area. • Generate randomly *n* nodes (uniform distribution). • Assume the transmission range of each node (usually all the nodes have the same range). • Find the neighbours according to the distance between nodes and the transmission range).
Step 1	Generate transmission requests randomly using Poisson distribution.
Step 2	For each request do the following: • Exclude the source and destination out of the nodes. • For the rest of the nodes, assume number of hops, starting from 1 hop (short route-source to destination route), 2 hops, find all combinations of one node out of $(n - 2)$ nodes, 3 hops, find all combinations of two nodes out of $(n - 2)$ nodes till $(n - 2)$ out of $(n - 2)$. In our model we stop at specific number of hops (3 hops in our simulation experiment). • For each combination of the previous step, find all the possible permutations.
Step 3	Check the validity of each route.
Step 4	Calculate the distance of each route, use the Euclidean distance.
Step 5	Pick the shortest distance route.
Step 6	Calculate the energy consumed by the nodes in the optimum route. • Case of source node: energy consumed only on transmission • Case of destination node: energy consumed for receiving only • Case of intermediate nodes: energy consumed in transmitting and receiving
Step 7	Calculate the consumed time and cost of the optimum route.
Step 8	Repeat from Step 2 till Step 7 for the rest of requests.
Step 9	Calculate the total consumed energy, total consumed time and total cost.

Figure 2 illustrates how the number of possible routes increases exponentially with the number of nodes in network topology. When the constraint of maximum hop count is six nodes we got almost 80,000 possible routes with 20 nodes topology. It will reach millions of possible routes if we relax (not consider) the maximum hop count constraint.

Figure 3 illustrates how the time is increasing exponentially with the number of nodes. In most of the applications, time is a big issue for the quality of service evaluation.

This model is based on basic mathematical formulas in a straightforward way and gives the results in a deterministic procedure without the use of any probabilistic equations. Therefore, it is considered as an exact reference model for the shortest route. Unfortunately, this reference model is impractical as it is seen from Figures 2 and 3.

Figure 2 Possible number of routes variation with node topology (see online version for colours)

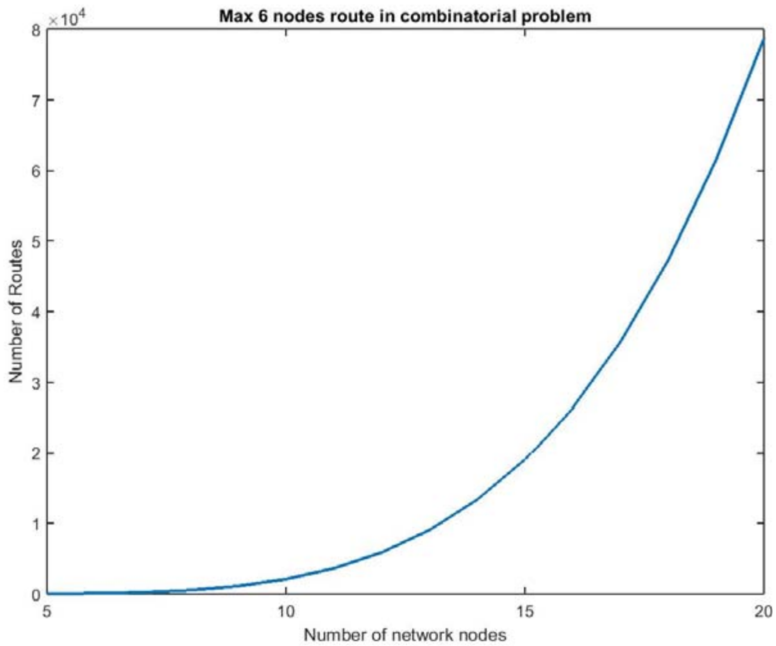
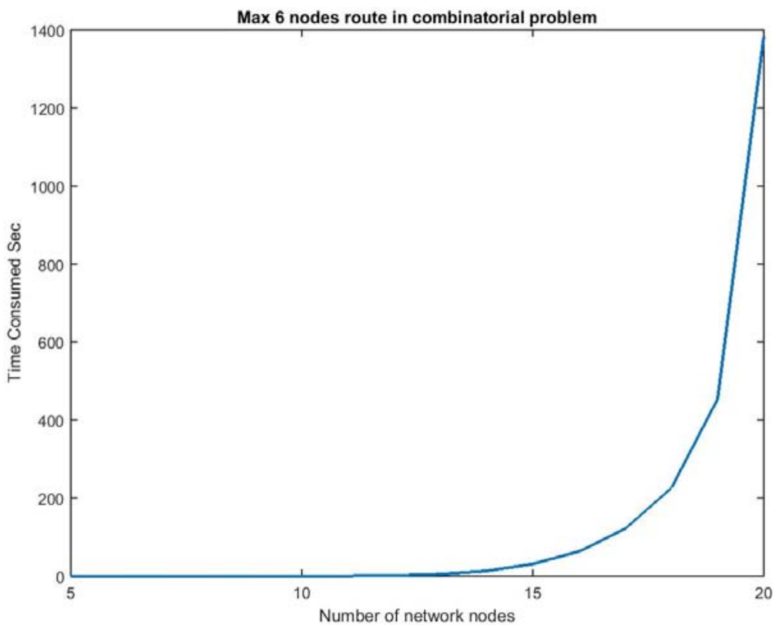


Figure 3 Variation of consumed time versus number of nodes in the network (see online version for colours)



3.2 Modified ACO

MANET is considered as a network type of undirected graph. Let $G = (V, E)$ represents a MANET, where V represents the set of network nodes and E denotes the set of bidirectional edges. In the simulation, the nodes are distributed uniformly in a given area, whereas the Poisson distribution is used to generate a sequence of requests. The maximum number of hops relies on the nodes intensity (number of nodes per unit area). The hop count is considered as an important issue because multiple hops are involved to transmit data from one place to another place in MANET. So it is required to find paths with minimum hops. Now the aim of the proposed algorithm is to find out a path that satisfies specific requirements such as energy saving, minimum cost, and minimum delay. Initially, delay adjacent matrix, and cost adjacent matrix are estimated. These measures depend upon the distance matrix. The distance between nodes is available only in the edges between nodes within transmission range neighbourhood.

When there is no neighbourhood relationship between two nodes, the pheromone substance on that link will be zero. As soon as neighbourhood relationship is established between two nodes, i and j, an initial pheromone amount 0.13 is deposited on that link as

$$\tau_{ij} = 0.13 \tag{1}$$

For each route, if the ant path through the link from node i to node j, the amount of pheromone is updated as follows:

$$\tau_{ij} = \tau_{ij} + \Delta\tau_{ij} \tag{2}$$

where $\Delta\tau_{ij} = 0.05$

The pheromone evaporation equation is:

$$\tau_{ij} = (1-\rho)\tau_{ij} \tag{3}$$

Path preference probability is calculated in both intermediate nodes as well as source nodes upon receipt of a route reply ant. Suppose current node i receives a route reply ant from node j for destination d then, the path preference probability is calculated as follows.

$$P_{ij} = \frac{[\tau_{ij}]^{\alpha}[D_{ij}]^{\beta}[\eta_{ij}]^{\gamma}[B_{ij}]^{\delta}}{\sum_{l\in N_i}[\tau_{il}]^{\alpha}[D_{il}]^{\beta}[\eta_{il}]^{\gamma}[B_{il}]^{\delta}} \tag{4}$$

where α, β, γ and δ (>=0) are tuneable parameters that control the relative weight of pheromone trail τ_{ij}, delay D_{ij}, hop count η_{ij} and bandwidth B_{ij} respectively Also, N_i is the set of neighbours of i and l is neighbour node of i through which a route is available to destination d.

The relative metrics are calculated using the following equations (5), (6) and (7) as when next hop on the path from i to the destination d is j.

$$D_{ij} = \frac{1}{\text{delay}(\text{path}(i, d))} \tag{5}$$

$$\eta_{ij} = \frac{1}{\text{hopcount}(\text{path}(i, d))} \tag{6}$$

$$B_{ij} = \text{bandwidth}(\text{path}(i, d)) \tag{7}$$

After finding the path preference probability through various neighbours, the source as well as intermediate nodes now have multiple paths to the destination. The path which has higher path preference probability will be selected for data transmission.

Modified ant colony algorithm is shown below.

Algorithm 2 Modified ant colony algorithm

Step 0 Topology design:

- Select the number of nodes (n) and the terrain area.
- Generate randomly n nodes (uniform distribution).
- Assume the transmission range of each node (usually all the nodes have the same range).
- Find the neighbours according to the distance between nodes and the node transmission range.

Step 1 Generate transmission requests randomly using Poisson distribution.

Step 2 For each request do the following:

- Define the input parameters:
  a cost adjacency matrix, delay adjacency matrix, S – source node, D – destination node, delay constraint, K – number of iterations, M – number of ants, α – characterisation of the importance of pheromone parameters, β – characterisation of the cost factor, γ – characterisation of the importance of the delay parameter, δ – characterisation of the importance of bandwidth parameter, τ – initial pheromone matrix, ρ – pheromone evaporation coefficient and Q – pheromone intensity increase factor.
- Initialise pheromone table.
- Pick a request and start to K wheel ants foraging activity of the destination node, each of iteration sends M ants.
- Initialise to the starting point of the current node.
- Route initialisation crawling.
- Crawling route delayed initialisation.
- Crawling route costs initialisation.
- Cost adjacency matrix backup – graph definition.
- Delay backup adjacency matrix – graph definition.
- You can go to the next node (optional set of nodes – neighbours to the current node)
- Choose how to go to the next step using probability distribution-as shown in the equation (4).
- Update and record status, increase path, cumulative path delay and cumulative cost path. Ants move to a next node, already visited node is removed.
- Write down the food line and the length of each line of each generation of ants.
- Update the pheromone table and update volume initialisation – pheromone update equation (2).
- After K iterations, confirm the selected route with the probability distribution.

Step 3	Calculate the energy consumed by the nodes in the optimum route. • Case of source node: energy consumed only on transmission • Case of destination node: energy consumed for receiving only • Case of intermediate nodes: energy consumed in transmitting and receiving
Step 4	Calculate the consumed time and cost of the optimum route.
Step 5	Repeat from Step 2 till Step 4 for the rest of requests.
Step 6	Calculate the total consumed energy, total cost and total consumed time.

The modified ACO algorithm is different from the original AntHocNet in the following points:

- It is a reactive protocol to eliminate the overhead of proactive procedure.
- The pheromone value is updated using forward ant only and not using the backward ant to decrease time overhead.
- The model parameters (α, β, γ, ρ, initial τ, Q, Dmax and K) are selected using a pre-processing phase (training phase) by running the model for a reasonable range of each parameter and fixing the other parameters to find the set of parameters that gives a best fit (matching) with the first exact (reference model). This training phase must be repeated for each different topology.
- The path preference probability P_{ij} to select next node depends on four QoS metrics (delay, hop count, bandwidth and the pheromone value).
- The consumed energy of each route is considered beside the execution time and the total cost as performance measurement criteria.

Figure 4 The influence of variation of ρ on the total consumed energy (see online version for colours)

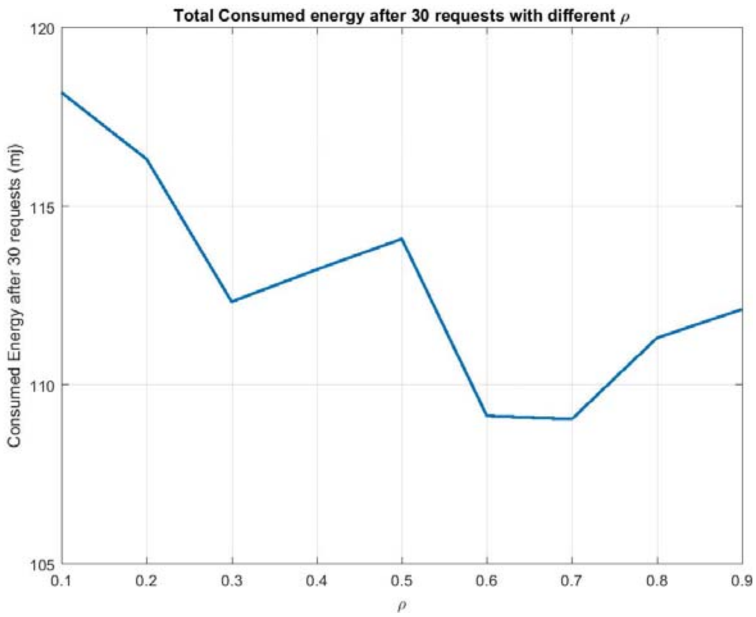
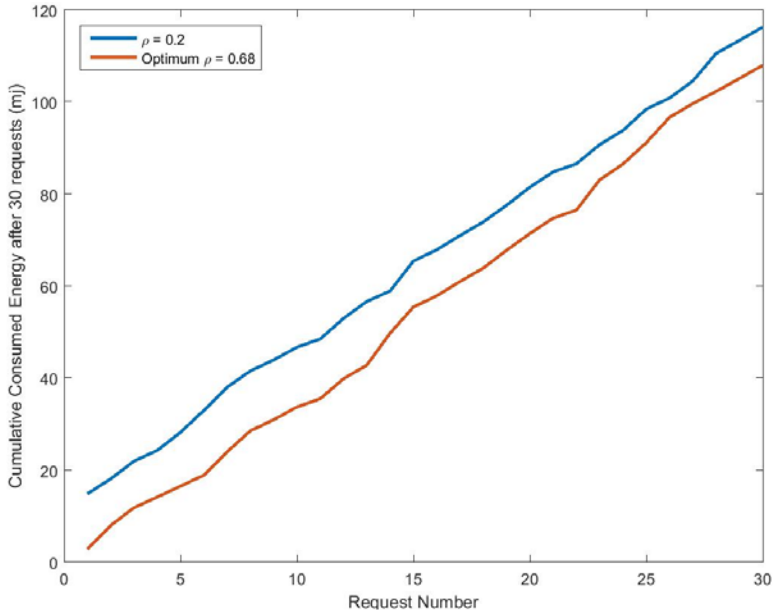


Figure 5 Comparison between the original AntHocNet (ρ = 0.2) and the modified ant colony (ρ = 0.68) (see online version for colours)



Figures 4 and 5 illustrate the importance of two modifications from the above, namely the pre-processing phase for parameter selection and the performance measurement for energy consumption evaluation.

Figure 4 shows the importance of one of the modifications concerning the pre-processing phase on just one parameter selection which is the pheromone evaporation coefficient ρ on the total consumed energy.

Figure 5 shows the cumulative consumed energy after 30 requests between the original AntHocNet and the modified ACO algorithm for the same inputs. It indicates that the modified ACO algorithm is better in energy consumption than the original one.

4 Simulation experiments

4.1 Experiment setup and parameters setting

The simulations are conducted in a 180×180 m^2 terrain area-two dimensional region. Fifteen nodes are assumed to be distributed uniformly. The coordinates of the nodes are randomly and uniformly distributed in this region. All nodes have the same bandwidth capacity B = 500. The nodes are assumed to be steady. All the nodes have the same initial energy 0.5 J. The transmission range of each node is 80 m. For each node group neighbour nodes within the same range are considered connected with edges together. The set of requests are generated by using Poisson function (i.e., the requests originating from a node follow the Poisson distribution). The packet size is considered to be fixed 2,000 bits.

Table 1 General parameter setting

Parameter	*Value*
Topology size	180×180 m^2
Nodes distribution	Uniform distribution.
Number of requests distribution	Poisson distribution
Transmission range	80 m
Bandwidth	500 bits per second
Initial energy	0.5 Joules
Packet size	2,000 bits

Table 2 Parameters setting for the modified ant colony model

Parameter	*Value*	*Parameter definition*
α	1	Characterises the importance of pheromone values
β	1	Characterises the heuristic cost factor
γ	.01	Characterises the heuristic delay factor
ρ	0.68	Pheromone evaporation coefficient
Initial τ	0.13	Initial pheromone value
Q	1	Pheromone intensity increase factor
Dmax	20	Maximum delay constraint
K	100	Maximum number of iterations

Table 2 shows the optimum parameters setting for the modified ant-colony algorithm. The maximum of iterations K = 100 represents the stopping criteria for ending the simulation experiment for each request. These set of parameters are selected for controlling the simulation experiment to find out the optimum configuration and performance. These parameters are estimated using a training model. Using this model, the best-fit parameters are evaluated.

4.2 Energy consumption analysis

In this work the proposed models use energy consumption model as described in the following equations (Kara, 2011). Total energy spent from source to destination is required to be as low as possible (El-Gazzar and Tawfik, 2013). The total consumed energy E_{total} can be calculated as follows:

$$E_{total} = E_a + E_t + E_r + E_c \tag{8}$$

where

E_a is the energy to survive

E_t is the energy required for packet transmission

E_r is the energy to retrieve a packet

E_c is the computation energy.

E_t is evaluated by equation (9).

$$E_t = E_{amp} \cdot d^{\alpha} \cdot b \quad (9)$$

where:

E_t is the energy sent by a node to transfer a series of bits

E_{amp} is a constant = 100×10^{-12} j/bit/m$^{\propto}$

d is the distance for packet transmission

α is packet loss constant (2 for the paths with no interference and 4 for the paths with interference)

b is the number of bits.

E_r is evaluated by equation (10).

$$E_r = E_{elec} \cdot b \quad (10)$$

where

E_r is the energy spent by a node to receive a packet

E_{elec} is a constant = 50×10^{-9} j/bit

b is the number of bits.

Since E_c and E_a given in equation (8) are used as constant values in other algorithms too, they can be neglected. The energy spent by a node to receive and transfer a packet is then approximately given by equation (11).

$$E_{total} = E_{amp} \cdot d^{\alpha} \cdot b + E_{elec} \cdot b \quad (11)$$

4.3 Analysis of the results and performance evaluation

Figure 6 shows the designed network topology for square terrain of 180×180 metres and 15 nodes whose locations are uniformly distributed and shown by their centres (x, y). All nodes are assumed to have the same transmission range of 80 metres and are shown as arcs from the circle ranges. This topology is fixed for both the proposed models.

Figure 7 shows the relationship between accumulated consumed execution time and the number of requests for the conventional combinatorial algorithm and modified ant colony algorithm. It is very clear from the figure that the ant colony algorithm is much better than the combinatorial one by approximately two orders of magnitude.

Table 3 gives the exact values of accumulated consumed times of both algorithms. For example after request 30 the consumed time for ant colony is *22.8483 seconds* while the consumed time for combinatorial is *3,137.4 seconds*.

Table 4 shows the produced optimum routes of the two algorithms for the whole set of 30 requests. It is noticed that the two algorithms are producing the same output routes in 13 requests (shown in grey rows). The rational errors are calculated in the last column. It is assumed that if the matching error is less than or equal 20%, it is considered identical. The percentage of matching is almost 77%.

Table 3 The execution time for both algorithms

Ser	*S*	*D*	*Combinatorial*	*Ant colony*
1	2	13	62.3	1.3297
2	5	8	136.8	2.2836
3	3	4	214.8	2.8603
4	10	8	294.8	3.6281
5	7	2	376.3	4.4473
6	7	11	457.1	5.2189
7	10	13	539.5	6.1149
8	8	5	621.5	6.9370
9	6	5	701.6	7.6269
10	1	6	782.8	8.2203
11	1	11	861.7	8.9320
12	3	5	939.8	9.7920
13	12	10	1,016.7	10.4552
14	7	13	1,095.4	11.4445
15	1	13	1,175.5	12.3233
16	14	2	1,254.1	12.9707
17	1	9	1,332.8	13.5541
18	1	10	1,412.2	14.1171
19	15	2	1,489.6	14.8983
20	2	15	1,567.4	15.7399
21	3	12	1,645.7	16.3374
22	8	12	1,724.6	17.1139
23	11	7	1,802.1	17.9723
24	15	4	1,914.0	18.5250
25	2	10	2,181.9	19.4053
26	14	11	2,265.3	20.1096
27	2	7	2,529.8	20.8547
28	4	13	2,783.4	21.6507
29	10	3	2,869.4	22.2795
30	4	15	3,137.4	22.8483

When we consider the second criteria of accumulated consumed energy as shown in Figure 8, it is clear that the total consumed energy of ant colony is greater than that of combinatorial algorithm.

Table 4 The output routes for both models

Ser	*S*	*D*	*Combinatorial*	*Ant colony*	*Rational error %*
1	2	13	2 → 11 → 13	2 → 11 → 13	0
2	5	8	5 → 4 → 6 → 8	5 → 12 → 11 → 8	0.7431
3	3	4	3 → 9 → 4	3 → 9 → 4	0
4	10	8	10 → 9 → 8	10 → 9 → 8	0
5	7	2	7 → 9 → 11 → 2	7 → 6 → 12 → 2	21.9984
6	7	11	7 → 9 → 11	7 → 6 → 11	3.5717
7	10	13	10 → 9 → 8 → 13	10 → 9 → 8 → 13	0
8	8	5	8 → 6 → 4 → 5	8 → 9 → 4 → 5	14.5067
9	6	5	6 → 4 → 5	6 → 4 → 5	0
10	1	6	1 → 12 → 6	1 → 4 → 6	27.9493
11	1	11	1 → 12 → 11	1 → 12 → 11	0
12	3	5	3 → 9 → 4 → 5	3 → 11 → 12 → 5	0.8342
13	12	10	12 → 4 → 10	12 → 5 → 4 → 10	70.1085
14	7	13	7 → 9 → 8 → 13	7 → 15 → 8 → 13	11.3737
15	1	13	1 → 12 → 11 → 13	1 → 4 → 6 → 11 → 13	25.5935
16	14	2	14 → 12 → 2	14 → 12 → 2	0
17	1	9	1 → 12 → 6 → 9	1 → 4 → 9	2.2597
18	1	10	1 → 4 → 10	1 → 4 → 10	0
19	15	2	15 → 6 → 11 → 2	15 → 8 → 11 → 2	5.5227
20	2	15	2 → 11 → 6 → 15	2 → 11 → 3 → 15	23.7686
21	3	12	3 → 11 → 12	3 → 11 → 12	0
22	8	12	8 → 11 → 12	8 → 6 → 12	7.4042
23	11	7	11 → 9 → 7	11 → 13 → 8 → 15 → 7	127.5627
24	15	4	15 → 9 → 4	15 → 9 → 4	0
25	2	10	2 → 12 → 4 → 10	2 → 12 → 4 → 10	0
26	14	11	14 → 4 → 6 → 11	14 → 12 → 11	7.6185
27	2	7	2 → 11 → 9 → 7	2 → 11 → 3 → 9 → 7	63.3180
28	4	13	4 → 6 → 8 → 13	4 → 9 → 8 → 13	16.6536
29	10	3	10 → 9 → 3	10 → 9 → 3	0
30	4	15	4 → 9 → 15	4 → 9 → 15	0

Figure 9 shows the relationship between total cost of route and the request number for both algorithms. From Figure 9, we conclude that the total cost of ant colony is greater than or equal the total cost of combinatorial model. It can be concluded also that we have high percentage of match.

Figure 6 Network input topology (see online version for colours)

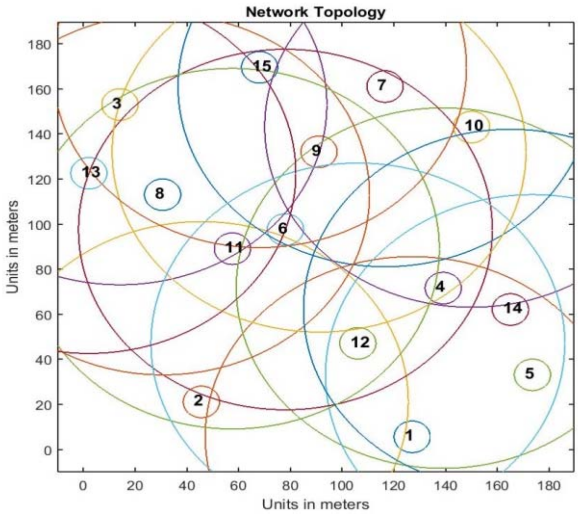
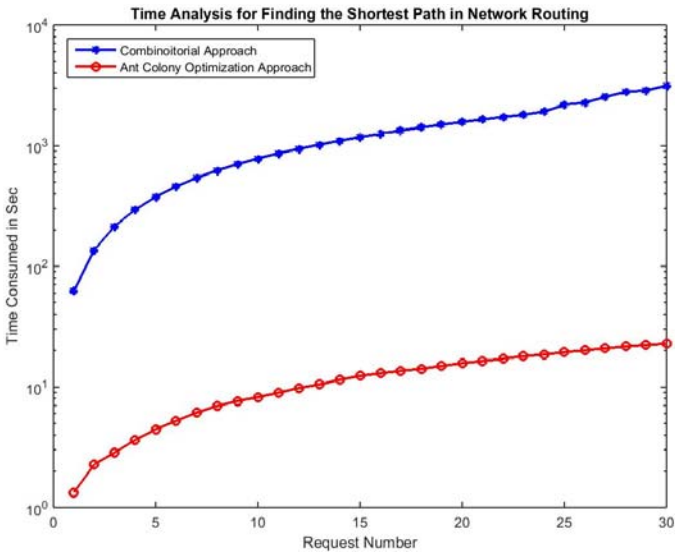


Figure 7 Time analysis for finding the shortest path (see online version for colours)



The first dead node for the conventional/combinatorial model occurs at request number 2,216, whereas for the modified ant colony, it occurs at request number 1,795. This result is logic because the exact solution comes up with minimum energy consumption. This is in turn increase the lifetime.

Figure 8 Total consumed energy for both models (see online version for colours)

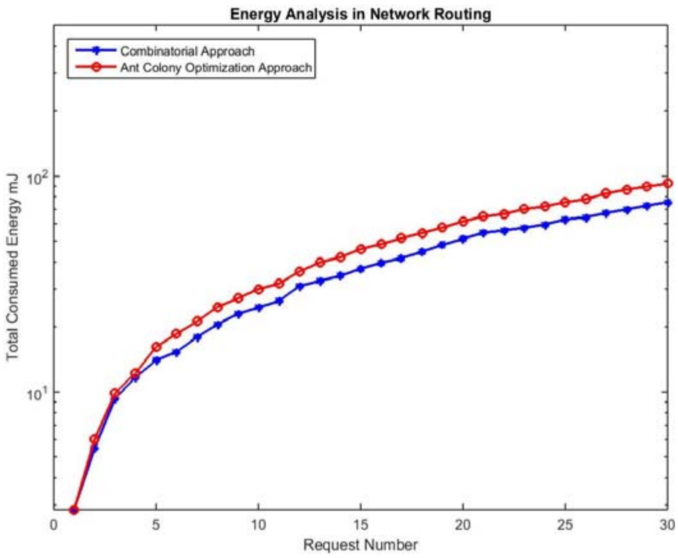


Figure 9 Total cost for both models (see online version for colours)

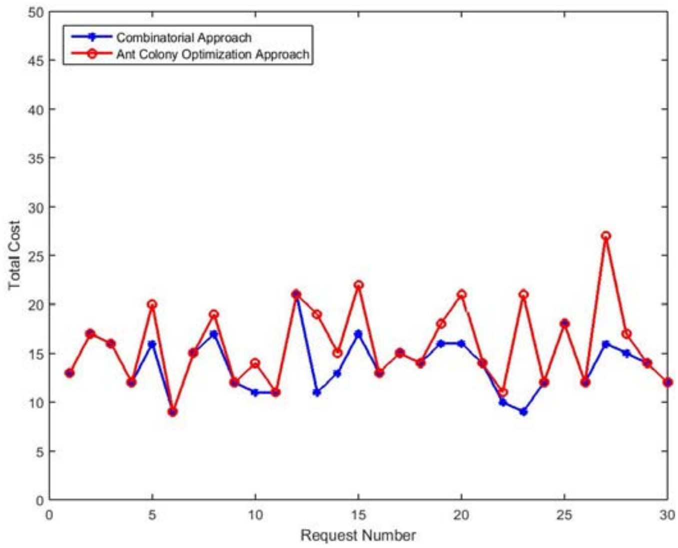
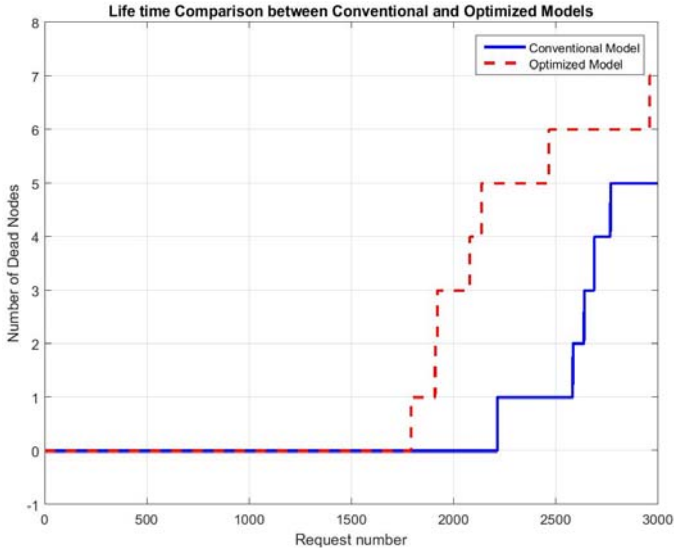


Figure 10 Lifetime comparisons between reference model and modified ACO (see online version for colours)



5 Conclusions

This paper contribution can be summarised in the following points:

1 Reference combinatorial model is developed using an exact mathematical formulas. This model is based on combinations and permutations to find all possible routes for a given request from a source node to destination node as a first step. At that step only one constraint concerning the maximum number of hop count is considered to limit the huge number of the obtained possible routes. As a second step a straightforward mathematical process is used to measure the route distance using Euclidean formula to find the shortest route from the set of all possible routes obtained at first step. Therefore, there is no any doubt in its process correctness (exactness). The output result (the shortest route) of this model is used as a reference (benchmark) to measure the correctness of other models with respect to the shortest route. Unfortunately, this model is impractical from execution time perspective since the time is increasing exponentially with the number of nodes in the topology.

2 To demonstrate the use of reference model in comparison study a modified ACO algorithm is proposed after some improvements:

- The pheromone value is updated using forward ant only and not using the backward ant to decrease time overhead.
- The model parameters (α, β, γ, ρ, initial τ, Q, $Dmax$ and K) are selected using a pre-processing phase (training phase) by running the model for a reasonable range of each parameter and fixing the other parameters to find the set of parameters that gives a best fit (matching) with the first exact (reference model). This training phase must be repeated for each different topology.
- The path preference probability P_{ij} to select next node depends on four QoS metrics (delay, hop count, bandwidth and the pheromone value).

3 The simulation experiments show that the modified ACO is giving approximately the same results as reference model in 77% of the requests with little increase in cost and consumed energy but it is much better in execution time which is interesting and promising results (almost more than 100 times saving).

4 The lifetime comparison between the reference model and modified ACO models shows that the reference model has better lifetime (less number of dead nodes) than modified ACO model since it has less energy consumption.

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