

Research Article

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Modeling and optimization of Quality of Service routing in Mobile Ad hoc Networks

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Abstract: Mobile ad hoc networks (MANETs) are a group of mobile nodes that are connected without using a fixed infrastructure. In these networks, nodes communicate with each other by forming a single-hop or multi-hop network. To design effective mobile ad hoc networks, it is important to evaluate the performance of multi-hop paths. In this paper, we present a mathematical model for a routing protocol under energy consumption and packet delivery ratio of multi-hop paths. In this model, we use geometric random graphs rather than random graphs. Our proposed model finds effective paths that minimize the energy consumption and maximizes the packet delivery ratio of the network. Validation of the mathematical model is performed through simulation.

Keywords: Mobile ad hoc networks (MANETs); multi-hop paths; Geometric Random Graph; Performance; Energy consumption

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1 Introduction

Mobile ad hoc networks are formed by mobile devices that are connected via wireless links when fixed networks are not applicable or not preferred [1]. Examples of applications of ad-hoc networks can be found in areas where earthquakes or other natural disasters have destroyed communication infrastructure, and for emergency

rescue and military operations. Some of the advantages of ad hoc networks are mobility, flexibility, scalability, the elimination of fixed infrastructure costs and the reduction of power consumption. In these networks, each node is equipped with a radio transceiver that allows it to communicate with others directly or indirectly [2, 3]. Each node has a limited transmission range and plays the role of a router for data packet destined for the other nodes. All nodes communicate directly in the transmission range of each other. In mobile ad hoc networks, each node moves independently in any direction, therefore, the network topology of MANETs can change frequently [4].

In recent years, mobile ad hoc networks have gained major attention from researchers. Various routing protocols for MANETs have been proposed. A routing protocol specifies how the source finds a route to the destination [2, 4]. Due to MANET's dynamic features, its limited resource (such as bandwidth and power energy), routing in these networks is extremely challenging. Therefore, it is difficult to design an effective routing protocol in the MANET.

Routing algorithms can be classified into three categories: proactive, reactive and hybrid. In proactive approaches each node in the network maintains a route to every other node in the network at all times. In these protocols a good route can be determined in the short response time due to the up to date network topology in each node. However, maintenance of the non-productive control packets in each node consume a large portion of network bandwidth. DSDV, Fisheye and WRP are protocols in this category. Reactive routing techniques, also called on-demand routing, create routes only when desired by the source node. Thus a node does not broadcast the routing table, thereby improving network bandwidth. However, a node may be waiting a long time before it can transmit the data packet. AODV, DSR, ABR and TORA are protocols in this category. The characteristics of proactive and reactive routing protocols can be integrated in various ways to form hybrid networking protocols such as zone routing protocol (ZRP) [5]. These approaches are discussed and compared in detail in [6].

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In ad-hoc networks the transmission range of nodes is limited. Thus, communication among them is often multi-hop. Fig. 1 demonstrates multi-hop communication in MANETs. The multi-hop communication is probably the most distinct difference between mobile ad hoc networks and other wireless communication systems, which makes communication possible between nodes out of transmission range of each other [7].

Wireless multi-hop networks impose many constraints than wired networks. Besides, the quality of service (QoS) of wireless networks, which specifies the services that a communication system provides, addresses a set of metrics such as delay, bandwidth, energy consumption and so on [8]. MANETs are characterized by dynamic topology and constraints on resources. Hence designing an effective routing protocol has become a popular research topic. Due to the advantage of numerical analysis, mathematical modeling has been widely used for performance analysis of communication systems. Mathematical modeling of QoS improves the decision making in ad hoc networks.

In this paper, we present a mathematical model for routing protocol. From the topology point of view, at any instant in time a mobile ad hoc network can be represented as a graph that vertices are the nodes of the network and edges are the links between the nodes. Two nodes are connected if there is a link between them. There are different graphical models for the study of network characteristics such as Erdos and Renyi random graph model, the regular lattice model, the scale-free model, and the geometric random graph model. These models are not equally suitable to characterize wireless multi-hop ad-hoc networks [7]. In this model, MANET is modeled using geometric random graphs rather than the classical random graph models. This model evaluates the packet delivery ratio and energy consumption of multi-hop paths in mobile ad hoc networks. We investigate the impact of packet delivery ratio of one-hop path and distribution of hop count of multi-hop path between a source node and a destination node on network performance. The presented model aims to identify paths that minimize the energy consumption and maximize the packet delivery ratio of the network from the source to the destination.

The rest of this paper is organized as follows. Section 2 reviews related works. In Section 3, the presented mathematical model for MANET is described in detail. Then we present a numerical example in Section 4. Section 5 provides a comparison of analytical results and simulation results and finally the conclusion is given in Section 6.

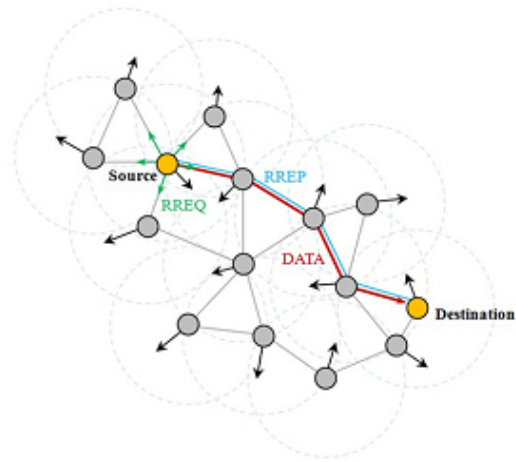


Figure 1: Communication among nodes in MANETs [11].

2 Related works

In design of mobile ad hoc networks with node mobility, performance evaluation is one of the important issues. The performance analysis can be determined by mathematical expressions of the number of neighbor nodes of a node and link duration between two nodes. In [9], Li and Yu have proposed the analytical and statistical models of the number of neighbor nodes based on the stochastic properties of nodes in mobile ad hoc networks. The results of their investigation show that the average number of neighbor nodes is almost linearly proportional to the node density in the region being studied, while the node density has no influence over the average distance between neighbor nodes. Wu *et al.* [10] have studied the impact of node mobility on link duration. They use relative velocity between two nodes and the distance that a node moves with that relative velocity until it is out of another node's radio range for presenting an analytical model for link duration. They have investigated the accuracy of their framework by simulation. The results of simulations show that their proposed model is suitable for the description of link duration in multi-hop mobile networks. Dung and An [11] have presented a detailed analytical model for evaluating the performance of multi-hop paths in mobile ad hoc networks. They use the stability of individual link and the distribution of hop count of multi-hop paths for presenting a closed-form model for packet delivery ratio of multi-hop paths. They have verified the analytical results via simulations in various settings of node mobility and network size.

In recent years, several studies have proposed efficient routing protocols for mobile ad hoc networks. Eom *et*

al. [12] have proposed an effective approximation method for QoS analysis of wireless cellular networks with impatient calls. Their approach is based on state space merging of two-dimensional Markov chains. In [13] Chang *et al.* have introduced an impressive color-theory-based energy efficient routing (CEER) algorithm for mobile wireless sensor networks. The proposed algorithm chooses a better, more energy-aware routing path by comparing the RGB value associated with neighboring nodes. Lee and Moon [14] have proposed mathematical models for a routing protocol under resource restrictions in a wireless sensor network. Their proposed model identifies energy-efficient paths that minimize the energy consumption of the network from the source sensor to the base station. Their proposed model can be applied to other network design contexts with resource restrictions.

Wang and Garcia-Luna-Aceves [15] have studied the performance of wireless multi-hop networks with a random access MAC protocol. They use a simple analytical model to derive the saturation throughput of collision avoidance protocols in multi-hop ad hoc networks, with nodes randomly placed according to a two-dimensional Poisson distribution. The results obtained show that the scalability problem of contention-based collision-avoidance protocols looms much earlier than people might expect. Alizadeh-shabdiz and Subramaniam [16] have presented an analytical model for the performance analysis of a single hop and multi-hop ad hoc network. Their approach is based on characterizing the behavior of a node by its state and the state of the channel it sees. They have used analysis of traffic loads of different nodes. Younes and Thomas [17] have presented an analytical framework for modeling and analysis of multi-hop ad hoc networks. The proposed framework is used to analyze the performance of multi-hop ad hoc networks as a function of network parameters, such as the transmission range, carrier sensing range, interference range, number of nodes, network area size, packet size, and packet generation rate.

In [18], Wang *et al.* have proposed an analytical model for performance analysis of wireless ad hoc networks using the network throughput and delay. In this model, the 802.11 DCF MAC protocol under finite load conditions is used at the MAC layer. In the proposed model, the hidden node problem was not considered. The simulation results show that this model predicts the throughput in wireless multi-hop networks accurately. Kumar *et al.* [19] have introduced an analytical model for estimating the average end-to-end delay of multi-hop ad hoc networks with the IEEE 802.11 DCF MAC protocol. This model has taken into account the packet arrival process, back-off and collision-avoidance mechanisms of random access MAC between

source and destination. This work has not considered the packet queuing delay. The proposed analytical model results and the simulation results match well.

There has been significant research carried out in the area of reliability analysis in wireless networks. The proposed algorithms are based on graph theory and Boolean algebra. In [20], Cook *et al.* have provided the description of the unique attributes of the mobile ad hoc wireless networks (MAWN) and how the classical analysis of network reliability can be extended to model and analyze dynamic networks such as MAWN. In this model, the reliability evaluation is performed by assuming the links to have fixed probability, *i.e.* considering the link existence as a probabilistic function. A network's reliability with this method can be determined quickly and can be balanced with cost and performance parameters. Chen *et al.* [21] have extended the ideas presented in [21]. They have calculated the two-terminal reliability of a MANET under the asymptotic spatial distribution of nodes. In this model, nodes move with Random Waypoint Mobility model which exhibits central tendency. They provided mathematical expressions for determining the one-hop and two-hop connectivity of the network and evaluated the two-terminal reliability using the sum of i -hop connectivity through $(n-1)$. They studied the impact of nodal density and nominal transmission ranges on the two-terminal reliability of a MANET using a simulation methodology. However, the computation of finding paths of three or more hops is cumbersome.

Padmavathy and Chaturvedi [22] have proposed a model to evaluate the network reliability of MANET through Monte Carlo Simulation. In this regard, the probability of successful communication depends on the robustness of the link between the mobile nodes of the network; reliability is calculated using a propagation-based link reliability model rather than a binary-model. In this model, MANET is represented as a fixed geometric random graph and the reliability of the network is evaluated by the reliability of a node pair in the path. The analytical results are verified via simulation in different scenario metrics such as network size, transmission range, network coverage area and propagation parameters on the MANET reliability.

3 Our proposed mathematical model

Here, we develop our mathematical model for evaluating the performance of multi-hop paths in mobile ad hoc networks. In this model, at any instant in time, MANET

can be represented as a lognormal geometric random graph rather than the classical random graph models of Erdos and Renyi. Geometric random graphs are graphs with distance dependent links between nodes and correlated links. An undirected geometric random graph with N nodes is denoted by $G_p(r_{ij})(N)$, where $p(r_{ij})$ is the probability of having a link between two nodes i and j at distance r_{ij} . The signal fading over a radio channel between a transmitter and a receiver can be dismembered into three components: large scale pathloss power, medium scale slow varying power and small scale fast varying amplitude. The large scale pathloss demonstrates the dependency of the expected received signal mean power to the distance between the transmitter and the receiver. The medium scale power variations are modeled with a lognormal distribution. The small scale signal fluctuations are represented by a Rayleigh distribution and are referred to as Rayleigh fading [7].

The realistic modeling of ad hoc networks is dependent on the selected model for the link probability between nodes. A more realistic geometric random graph model will be made by taking the medium scale radio signal power variations into account. Due to the dependency of the link probability on the lognormal radio propagation, this model is called the lognormal geometric random graph model. With regard to a wireless ad hoc network, the connections depend on the distance between nodes and links are locally correlated. The lognormal geometric random graph matches the characteristics of ad hoc networks better than other models [7]. In this model, N nodes are uniformly distributed over a square area of dimension $m \times n$, in which the nodes move according to the Random WayPoint (RWP) [23] mobility model. Links are formed between nodes using the link probability of the lognormal model that is defined as follows [7]:

$$p(\hat{r}_{ij}) = \frac{1}{2} \left[1 - \operatorname{erf} \left(v \frac{\log \hat{r}_{ij}}{\xi} \right) \right] \quad \xi \triangleq \frac{\sigma}{\eta} \quad (1)$$

$$v = \frac{10}{(\sqrt{2} \log_2 10)} \quad (2)$$

Where $\hat{r}_{ij}$ is the normalized distance between node i and node j , and ξ is the ratio between the standard deviation of radio signal power fluctuations, σ , and the pathloss exponent, η . Low values and high values of ξ correspond to small power variations and stronger power variations, respectively. When $\xi > 0$, nodes at a distance larger than one, are connected with a non-zero probability, also nodes at a distance less than one, are disconnected with a non-zero probability.

A node is another node's neighbor if it is located within the transmission range of that node. The neighbor

nodes can send and receive packets to each other successfully.

In our proposed model, the performance of a multi-hop path is derived from two factors: the packet delivery ratio multi-hop path and energy consumption [14] of the network. Due to the dynamic nature of the MANETs, packet delivery ratio is a QoS requirement. Also, as these networks are characterized by limited resource such as energy, it is necessary to conserve the energy of the nodes. In fact, the proposed model finds the best path that guarantees the quality of service. Two factors of quality of service in this model are in contradiction and our proposed model aims to maximize the packet delivery ratio and minimize the energy consumption of the network. We select multi-criteria formulation in our model in ad hoc networks, which can be represented as follows. In this formula, Pdr and E_i are packet delivery ratio and energy of node i , respectively.

$$\begin{cases} \min & \sum_{i \in N} e_{i0} - \sum_{i \in N} E_i \\ \max & Pdr \end{cases} \quad (3)$$

3.1 Energy consumption

In this model, we consider the energy used during information transmission that include message sending and message receiving [14, 24]. We assume that the initial energy of each node is the same and that the energy consumption is in direct proportion to the distance between the nodes. Keeping in mind that nodes have limited available energy, the objective of the proposed model is to minimize the energy consumption that is formulated as follows:

$$\min \sum_{i \in N} e_{i0} - \sum_{i \in N} E_i \quad (4)$$

Subject to:

$$\sum_{\substack{i \in N \\ i \neq k}} X_{ik} - \sum_{\substack{j \in N \\ j \neq k}} X_{kj} = 0 \quad \text{all } k \in N, k \neq s, k \neq d, \quad (5)$$

$$X_{ij} + X_{ji} \leq 1 \quad \text{all } i, j \in N, i \neq j, \quad (6)$$

$$\sum_{\substack{j \in N \\ j \neq s}} X_{sj} = 1 \quad (7)$$

$$\sum_{\substack{j \in N \\ i \neq d}} X_{id} = 1 \quad (8)$$

$$d_{ij}X_{ij} \leq R, \quad (9)$$

$$E_i - e_{i0} + cr \cdot \sum_{\substack{j \in N \\ i \neq j}} X_{ij} = 0 \quad i = d, \quad (10)$$

$$E_i - e_{i0} + ct \cdot \sum_{\substack{j \in N \\ i \neq j}} d_{ij}X_{ij} + cr \cdot \sum_{\substack{j \in N \\ i \neq j}} X_{ij} = 0 \quad (11)$$

$$\text{all } i \in N, i \neq d,$$

$$X_{ij} \in \{0, 1\} \quad \text{all } i, j \in N, \quad (12)$$

$$E_i \geq 0 \quad \text{all } i \in N. \quad (13)$$

Where all the notations used in the above equations are explained in Table 1.

Constraint (5) shows that the total flow from node i to node k is equal to the total flow from node k to node j except in the source and destination nodes. In constraint (6), sub-tours are eliminated. Constraints (7) and (8) illustrate that the flow must be out of the source node and into the destination node. Constraint (9) shows limits on the interconnect distance. Constraints (10) and (11) define the remaining energy of the destination node and the other nodes, respectively. The decision variable X_{ij} in constraint (12) takes a value of 0 or 1 and in constraint (13) the decision variable E_i is a non-negative value.

Table 1: The used notations.

Indices	Description
i, j, k	Indices of node
N	Number of nodes
s	Source node index
d	Destination node index
d_{ij}	Distance from node i to node j
e_{i0}	Initial energy of node i
ct	Rate of energy consumption during transmission
cr	Rate of energy consumption during reception
X_{ij}	$\forall i, j \in N \begin{cases} 1 & \text{if node } i \text{ and } j \text{ are linked} \\ 0 & \text{otherwise} \end{cases}$
E_i	Energy of node i
R	The distance where the area mean power is equal to the receiver sensitivity

3.2 Packet delivery ratio of multi-hop path

The packet delivery ratio of a multi-hop path is dependent on the average packet delivery ratio of individual links and the average number of hop counts in the path [11]. The link existence between any pair of nodes is independent of the others because each node moves independently. Thus the packet delivery ratio can be calculated by multiplying the average packet delivery ratio of each individual link [11], that is shown by following equation:

$$per_k = \overline{per}_1 \times \dots \times \overline{per}_k = \prod_{i=1}^k \overline{per}_i. \quad (14)$$

Where per_k is the packet delivery ratio of k -hop path and $\overline{per}_i$ is the average packet delivery ratio of an individual link between node i and node $i+1$.

Average packet delivery ratio of individual links

We calculate the average packet delivery ratio of an individual link from the link duration of a node and its neighboring node. The duration of time that two nodes will remain connected can be determined by the motion parameters such as speed, direction and transmission range. In this approach, we assume the received signal strength only depends on its distance to the transmitter. Therefore, the amount of time two nodes stay connected can be calculated as follows [25]:

$$D_t = \frac{-(ab + cd) + \sqrt{(a^2 + c^2)r^2 - (ad - bc)^2}}{a^2 + c^2}, \quad (15)$$

Where

$$a = v_i \cos \theta_i - v_j \cos \theta_j, \quad (16)$$

$$b = x_i - x_j, \quad (17)$$

$$c = v_i \sin \theta_i - v_j \sin \theta_j, \quad (18)$$

$$d = y_i - y_j. \quad (19)$$

Where (x_i, y_i) is the coordinate of node i and (x_j, y_j) is the coordinate of node j . v_i and v_j are the speed, and θ_i and θ_j are the moving direction of node i and node j , respectively. When $v_i = v_j$ and $\theta_i = \theta_j$, D_t becomes infinity.

Data packets are successfully transmitted if the link between a node and its neighboring nodes exists. Otherwise, data packets cannot be successfully transmitted. We assume that data packets are sent with a constant rate.

Hence, the number of sent/received data packets is linearly proportional with time (t). Therefore, the packet delivery ratio of individual links is obtained by the following equation:

$$\overline{per}_i = \begin{cases} 1 & 0 \leq t \leq D_t \\ 0 & 0.W \end{cases}. \quad (20)$$

Average number of hop count in the path

We assume that nodes move in a square area with a certain length and width. According to equation (16) in [26], the cumulative distribution function of distance L between two nodes that are uniformly distributed is:

$$P(L \leq l) = \frac{1}{2} \left(\frac{l}{a} \right)^4 - \frac{8}{3} \left(\frac{l}{a} \right)^3 + \pi \left(\frac{l}{a} \right)^2 \quad (21)$$

$$(0 \leq l \leq a),$$

$$P(L \leq l) = 2 \left(\frac{l}{a} \right)^2 \arcsin \left(\frac{a}{l} \right) \quad (22)$$

$$- 2 \left(\frac{l}{a} \right)^2 \arccos \left(\frac{a}{l} \right) + \frac{8}{3} \left(\frac{l}{a} \right)^2 \sqrt{\left(\frac{l}{a} \right)^2 - 1}$$

$$+ \frac{4}{3} \sqrt{\left(\frac{l}{a} \right)^2 - 1} - 2 \left(\frac{l}{a} \right)^2 - \frac{1}{2} \left(\frac{l}{a} \right)^4$$

$$(a \leq l \leq \sqrt{2}a).$$

Hop count can be considered as a discrete random variable k , because the hop count of a link is an integer value that can be obtained from the distance of two nodes and their transmission range [11]. Thus the probability mass function of a random variable k can be written as follows:

$$p_k(k) = \begin{cases} P(L < R) & k = 1 \\ P(L < 2R) - P(L < R) & k = 2 \\ P(L < 3R) - P(L < 2R) & k = 3 \\ P(L < 4R) - P(L < 3R) & k = 4 \\ \dots & \dots \\ P(L < \sqrt{2}a) - P\left(L < \left\lceil \frac{\sqrt{2}a}{R} - 1 \right\rceil R\right) & k = \left\lceil \frac{\sqrt{2}a}{R} \right\rceil \end{cases} \quad (23)$$

Where R and a are the radio range of nodes and the network size, respectively. L is the distance between two uniformly distributed nodes.

The closed-form model

We combine the results obtained from equations (20) and (23) with equation (14) to calculate the final closed-form for the packet delivery ratio of multi-hop paths in mobile ad hoc networks. This is given by the following equation:

$$Pdr = (\overline{per}_1) \times p_1(1) + (\overline{per}_1 \times \overline{per}_2) \times p_2(2) + \dots \quad (24)$$

$$+ \left(\overline{per}_1 \times \dots \times \overline{per}_{\left\lceil \frac{\sqrt{2}a}{R} \right\rceil} \right) \times p_{\left\lceil \frac{\sqrt{2}a}{R} \right\rceil} \left(\left\lceil \frac{\sqrt{2}a}{R} \right\rceil \right)$$

$$= \sum_{k=1}^{\left\lceil \frac{\sqrt{2}a}{R} \right\rceil} \left\{ \prod_{i=1}^k \overline{per}_i \right\} \times p_k(k).$$

4 Numerical example and performance evaluation

In this section, we consider two numerical examples. Simulations are carried out using the TrueTime toolbox of MATLAB software. TrueTime is a Matlab/Simulink-based simulator for controller task execution in real-time kernels, network transmissions and continuous plant dynamics. Using TrueTime it is possible to simulate the temporal aspects of multi-tasking real-time kernels and wired or wireless networks within Simulink, together with the continuous-time dynamics of the controlled plant [27].

In our experiments we consider a fixed network size of $50 \times 50 \text{ m}^2$ in which 10 nodes are uniformly distributed in the network. We have formed links between nodes using the link probability of the lognormal geometric random graph model. The graphical configurations of the network are shown in Fig. 2(a) and Fig. 3(a). Tables 2 and 3 show the distance data for the pairs of nodes in Figs. 2 and 3 respectively, which are calculated based on Euclidean distance.

In the experiment we assign the same initial energy value of each node ($e_{i0} = 10$) and set the rate of energy consumption during transmission and reception ($ct = cr = 0.1$) for the mobile nodes. In both examples, we suppose that node 1 and 9 are the source and destination, respectively. The comparison between the optimal route and the feasible routes in the network in terms of the total distance, total energy consumed and performance is shown in Tables 4 and 5 for Figs. 2 and 3, respectively. The graphical optimal route between node 1 and node 9 is shown in Fig. 2(b) and Fig. 3(b) by red color.

Table 2: Distance matrix for Fig 2.

$\begin{smallmatrix} i \\ j \end{smallmatrix}$	1	2	3	4	5	6	7	8	9	10
1	0	8.12	10.15	10.21	4.74	12.41	9.65	15.1	13.03	16.24
2	8.12	0	7.53	9.33	4.15	5.81	7.66	8.32	10.3	8.6
3	10.15	7.53	0	16.36	6.17	5.27	0.73	15.18	3.06	9.47
4	10.21	9.33	16.36	0	10.66	15	16.28	9.08	19.34	16.65
5	4.74	4.15	6.17	10.66	0	7.67	5.89	12.28	9.23	11.56
6	12.41	5.81	5.27	15	7.67	0	5.91	11.11	6.52	4.35
7	9.65	7.66	0.73	16.28	5.89	5.91	0	15.51	3.40	10.15
8	15.1	8.32	15.18	9.08	12.28	11.11	15.51	0	17.39	10.28
9	13.03	10.3	3.06	19.34	9.23	6.52	3.40	17.39	0	9.98
10	16.24	8.6	9.47	16.65	11.56	4.35	10.15	10.28	9.98	0

Table 3: Distance matrix for Fig 3.

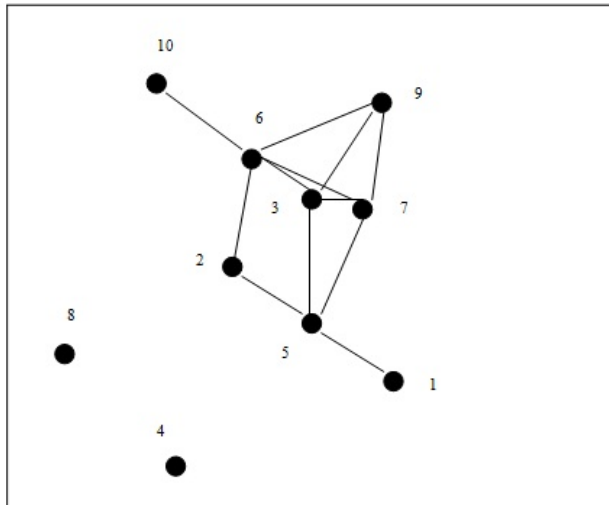
$\begin{smallmatrix} i \\ j \end{smallmatrix}$	1	2	3	4	5	6	7	8	9	10
1	0	12.37	22.09	25.06	24.41	12.21	20.62	10.44	22.09	33.62
2	12.37	0	11.18	18.03	23.09	24.17	29.73	15.81	26.93	32.39
3	22.09	11.18	0	10	19.7	32.39	34.48	26.62	28.28	27.46
4	25.06	18.03	10	0	11.31	32.39	30.81	19.11	22.36	17.72
5	24.41	23.09	19.7	11.31	0	27.29	22.02	14.87	12.17	9.49
6	12.21	24.17	32.39	32.39	27.29	0	12.17	13.34	19.21	34.83
7	20.62	29.73	34.48	30.81	22.02	12.17	0	14.21	10.44	26.93
8	10.44	15.81	26.62	19.11	14.87	13.34	14.21	0	12.04	23.60
9	22.09	26.93	28.28	22.36	12.17	19.21	10.44	12.04	0	16.55
10	33.62	32.39	27.46	17.72	9.49	34.83	26.93	23.60	16.55	0

Table 4: Comparison between the optimal route and the feasible routes for Fig. 2.

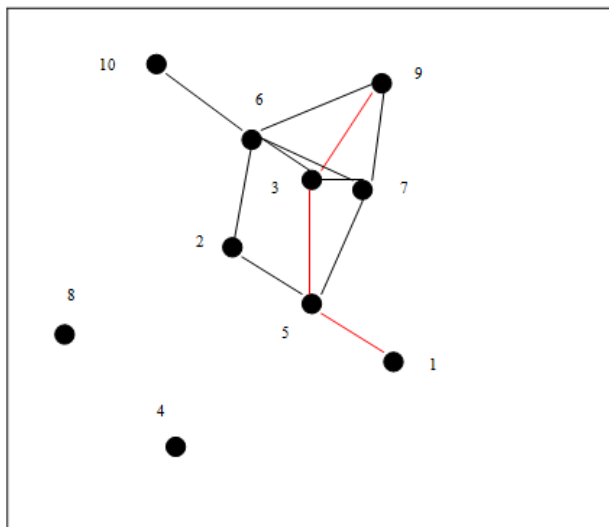
	Total distance	Total energy consumed	Performance
Optimal route (1 5 3 9)	13.97	4.6	0.31
Feasible route (1 5 7 9)	14.03	4.76	0.31
Feasible route (1 5 2 6 9)	21.22	5.83	0.48
Feasible route (1 5 2 6 3 9)	23.03	7.57	0.65
Feasible route (1 5 2 6 7 9)	24.01	7.71	0.65

Table 5: Comparison between the optimal route and the feasible routes for Fig. 3.

	Total distance	Total energy consumed	Performance
Optimal route (1 8 9)	22.48	6.05	0.24
Feasible route (1 6 7 9)	34.82	7.94	0.33
Feasible route (1 2 3 4 5 9)	57.03	15	0.68



(a)



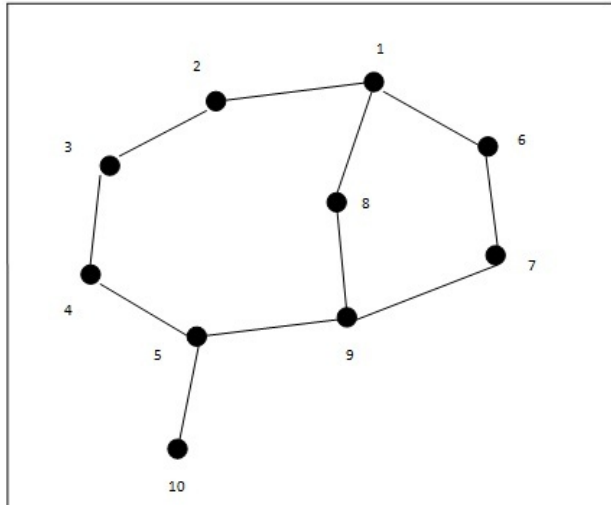
(b)

Figure 2: (a) The graphical configuration of the network. (b) The optimal route.

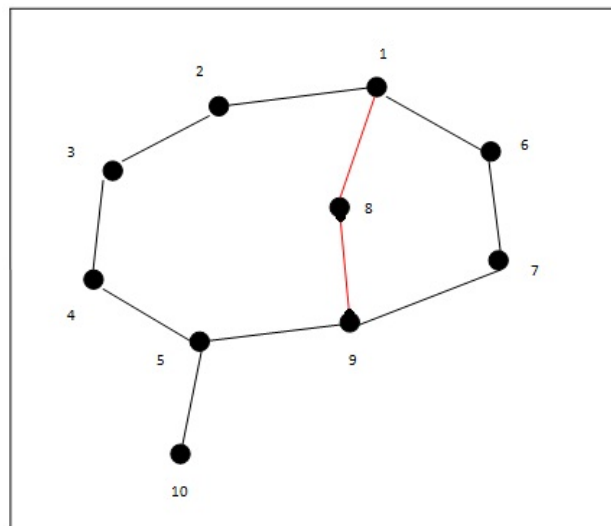
5 Performance evaluation

The network performance is simulated using the Matlab/Simulink-based simulator TrueTime. We consider a network size of $100 \times 100 \text{ m}^2$ by increasing the number of nodes from 10 to 40. In experiments, mobile nodes move under the RWP mobility model. With regard to the proposed model which can be applied to any routing protocol, we use the AODV routing protocol in simulations.

The following criteria are used for comparison of analytical results and simulation results:



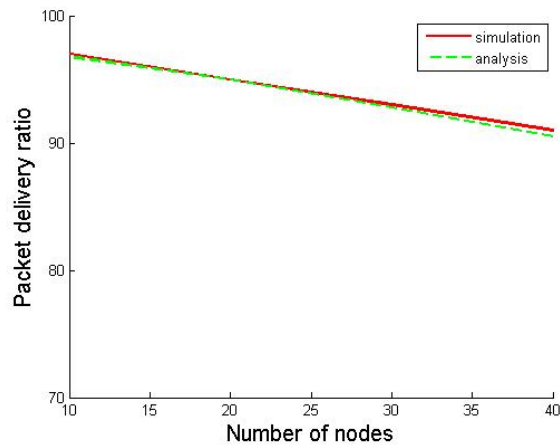
(a)



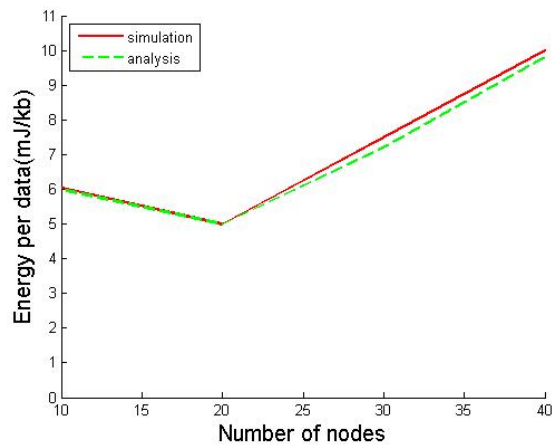
(b)

Figure 3: (a) The graphical configuration of the network. (b) The optimal route.

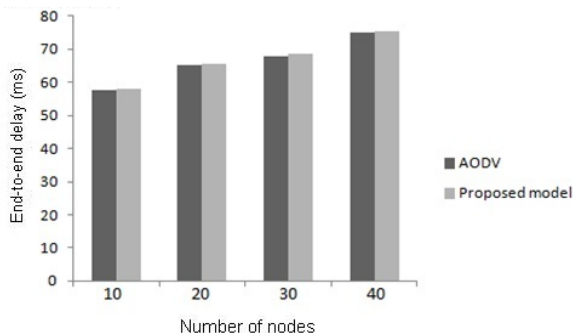
- Packet delivery ratio: the ratio between the number of packets successfully received by the application layer of a destination node and the number of packets originated at the application layer of each node for that destination.
- Energy expenditure: energy consumed in transporting one kilo-byte of data to its destination.
- Delay: time interval once a data packet is generated by the application of a node and when it is delivered to the application layer of a destination node.



(a) Packet delivery ratio



(b) Energy per user data



(c) End-to-end delay

Figure 4: Comparison of results

The results obtained are represented in Fig. 4. As we can see in Figs. 4a and 4b, the analysis result and simulation result of packet delivery ratio and energy expenditure closely match. Despite the mathematical computation in

the proposed model, Fig. 4c shows that the end-to-end delay of the proposed model is approximately the same as compared to AODV.

6 Conclusions

In this paper, we have presented a mathematical analysis model for performance analysis of multi-hop paths in mobile ad hoc networks, where nodes move according to the RWP mobility model. In the presented model, we used the lognormal geometric random graph model for establishing links between nodes. The presented model consists of two parameters: packet delivery ratio and energy consumption. In computing the required performance indices, the proposed model minimizes the energy consumption and maximizes the packet delivery ratio. We showed how the packet delivery ratio of multi-hop paths is determined by the packet delivery ratio of one-hop paths and the distribution of hop count of multi-hop path between a source node and a destination node. The simulation results using MATLAB software demonstrate that the analytical and simulation results match well and the proposed algorithm selects the optimum multi-hop path. Further research will focus on developing our proposed model to support other QoS requirements such as security and privacy.

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