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ORIGINAL ARTICLE

Developing a bi-objective model for a reliable mobile ad hoc network routing problem

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Abstract Nowadays, mobile ad hoc networks (MANET), which consist of a set of mobile nodes communicate with each other wirelessly, are considerably attended. In the last decades, with regard to different considerations, data routing problem has been studied as a main issue, widely. In these networks, developing models which lead to a more economic and confident route has always been a desired target. Hence, in this paper, a bi-objective mathematical model for MANETs routing problem is proposed, which aims to minimize energy consumption of data transmission and maximize reliability of selected route, simultaneously. To define reliability of the network, failure rate of each link is considered. To solve the proposed bi-objective mathematical model, a L_p-metric method is used which transforms the model to a single one. Finally, a numerical example is used to evaluate the efficiency of proposed model. The results indicate adding reliability criterion as the second objective function leads to a more confident and efficient solution, which is based on both energy consumption and reliability criteria.

Keywords Mobile ad hoc networks · Reliability · Energy consumption · Routing problem

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1 Introduction

Nowadays, improvement of mobile and wireless networks makes communication more effective than wired networks. Unlike the traditional wired networks, in these networks the nodes are not connected by cables. Use of a wireless network enables consumers to avoid the costly problems of communication process such as users' mobility, equipment portability, etc. A wireless local area network (WLAN) can operate in both infrastructure and ad hoc modes.

In an infrastructure mode, nodes link to each other indirectly, through some access points (APs), while wireless ad doc networks are decentralized networks in which each node can forward data packets to the other nodes, directly. The main objective of an ad hoc network is to maintain the node's connectivity and transport the data packets reliably (Guerriero et al. 2009). One of ad hoc networks, which has been attended recently, is Mobile Ad hoc Network (MANET). A MANET is a set of mobile hosts that can communicate with each other without using base stations (Fig. 1). The topology of a MANET can be very dynamic due to the mobility of mobile nodes.

In dynamic and mobile wireless networks, selecting a route which considers limitations of a network such as loss rate of the packets, energy considerations, transferring time constraints, etc., is a challenging problem (Saleem et al. 2010). Various researches with different metrics have been proposed for routing problem in MANETs. Wang et al. (2007) studied the relationship between the total power spent in the whole network and power transmission range. Moussaoui et al. (2014) presented a model to optimize energy consumption in a MANET regarding stability of links connected nodes. The distance among nodes has been regarded as an effective factor to evaluate stability of the links beside energy consumption in routing problem by

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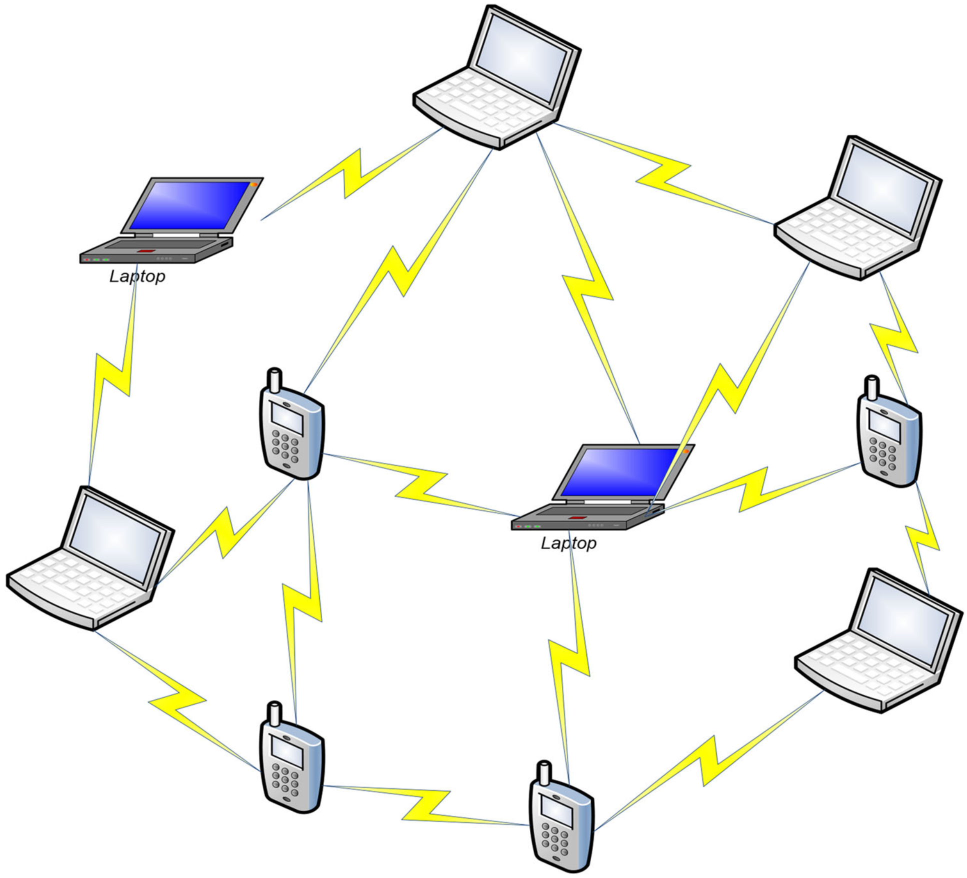

Fig. 1 A typical mobile ad hoc network (MANET)

Guerriero et al. (2009). The transmitting and receiving capabilities of nodes have been considered in a routing problem of MANET regarding energy consumption in Gua and Zhu (2013). Son et al. (2014) studied the environmental changes of networks in routing protocols. Mukherjee et al. (2007) concentrated on a self-stabilizing energy-efficient multicast method for MANETs. Le et al. (2009) proposed a transport protocol for data streaming in wireless network based on energy-efficiency and reliability. An energy aware routing approach for mobile ad hoc network problems is presented by Guo et al. (2011). Daranasi et al. (2012) analyzed the performance of different MANET routing protocols regarding their performance in different mobility models. Dash and Balabantaray (2014) proposed a routing protocol for MANET and used a metaheuristic algorithm called ant colony optimization to solve the proposed model. Alotaibi and Mukherjee (2012) surveyed some routing algorithms for wireless ad hoc networks.

According to the mentioned researches and many other studies in MANET routing problems, one can conclude that energy consumption is one of the most significant criteria in MANET routing problems (Lloyd et al. 2005). If the amount of the consumed energy exceeds the maximum level, interfacing of the nodes among the network could be harmed. Indeed, the lifetime of a network can be affected by the required energy consumed during transferring data through the entire networks (Saleem et al. 2010). Hence, finding a route among nodes that leads to less energy consumption is still an attractive criterion in MANET routing problems.

In this paper a mathematical model is developed for a MANET routing problem which, as the main goal, aims to minimize the total energy consumption. The basic model for energy consumption consideration is based on the model proposed in Guerriero et al. (2009). In addition to this common and traditional objective function, selecting a more reliable route, which improves confidence of network, is considered as another metric to evaluate the goodness of the solution for routing problem. To calculate the reliability of each route, the probability of losing data during passing among links of network is attended. Hence, this paper proposed a bi-objective mathematical model for a MANET routing problem in which the main contributions against previous works can be presented as follows:

1. Reliability of each route, calculated based on failure rate of the links make that route, is considered as a criterion in MANET routing problem. This consideration leads to a more confident decision making in routing problem.

2. Although most of the previous works just concentrated on a single metric in MANET routing problem, in this paper a bi-objective model is developed, in which both energy consumption and reliability of the routes are considered, simultaneously as two different and opposite metrics evaluate good routes.

The rest of this paper is organized as follows: In Sect. 2, a bi-objective mathematical model for MANET routing problem is formulated and proposed solving approach is presented. A numerical example is solved in Sect. 3. Finally, the conclusion and future researches are discussed in Sect. 4.

2 Problem formulation

Assume a wireless ad hoc network modeled as a directed graph $G = (N, L)$, where N is set of nodes and L is set of links (i,j) with $i,j \in N$. The link (i,j) exists if and only if $j \in N_i$, where N_i denotes neighbors of node i. In other word N_i is the set of all nodes can be reached by node i with respect to its transmission range, that is $N_i = \{j \in N | t_{ij} \leq R_i\}$ where R_i represents the transmission radius of node i and t_{ij} denotes the time distance between node i and j (Fig. 2).

Let S denotes the source node and D represents the destination node. The problem is selecting the best route among numerous routes between these two nodes at a given time by considering energy consumption and reliability of the route, simultaneously. Next subsections describe these criteria.

2.1 Energy consideration

To minimize the energy consumption, the route with less energy consumption should be selected. To calculate the energy consumption of each link on a route, Eq. (1) can be used, as proposed by Guerriero et al. (2009).

$$P_{ij}(t) = \beta \times t_{ij}^{n} \times f \quad (1)$$

where $P_{ij}(t)$ denotes the energy consumed during transferring data at a given of time (t), f is the rate of data should be sent to destination node, n is the pass loss index

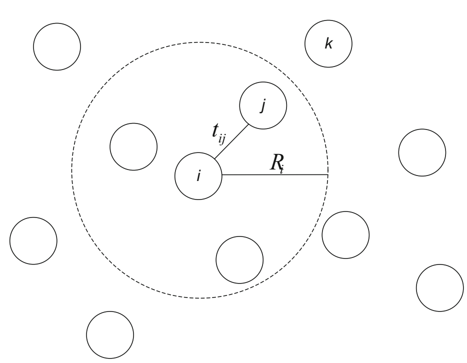

Fig. 2 Transmission radius of node i

and $2 \leq n \leq 4$, t_{ij} denotes transferring time duration between node i and j and β represents a time distance-related coefficient (Guerriero et al. 2009).

In other side, the desirability of each node j to be selected as neighbor of transmitter node i can be calculated by Eq. (2).

$$D_j(t) = \frac{E_{\text{res}}}{E_j^{(0)}} \quad (2)$$

where $D_j(t)$ represents desirability of node j to receive data from another node at time t, $E_j^{(0)}$ represents its initial energy and E_{res} is its residual energy.

Based on these mentioned criteria, energy consumption metric $m_{ij}(t)$ can be calculated using Eq. (3), for each link at given time t.

$$m_{ij}(t) = \frac{P_{ij}(t)}{D_j(t)} \quad (3)$$

As a result, it is obvious that links with less energy consumption and more residual energy are more desired to be selected. In this paper, minimizing total energy consumption is considered as the first objective function of the routing problem.

2.2 Reliability consideration

To consider reliability criterion in this model, packet loss probability is regarded, which usually can be a result of network congestion and node's mobility in wireless sensor networks.

Assume that the data should be transmitted from source node S to destination node D and there is a route, p, with m links among these two nodes. If p_{ij} denotes the probability of failure in forwarding data from node i to node j for link $(i,j) \in p$, the reliability of this link can be computed by Eq. (4):

$$r(i,j) = (1 - p_{ij}) \quad (4)$$

According to Eq. (4), a link with less loss rate is more reliable. Furthermore, during passing route p, a sent packet from node S will be received at node D, if all links of route p operate properly. Therefore, the reliability of entire route p can be calculated by Eq. (5):

$$r_T(p) = \prod_{(i,j) \in p} r(i,j) \quad (5)$$

This reliability criterion is considered as the second metric in routing problem.

2.3 Constraints

There are some constraints in transferring data through links which limit the model. These constraints are considered as follows:

2.3.1 Transmission time limitation

In this paper, it is assumed that wasted time to transmit data from source node S to end node D should be less than time T. This constraint can be formulated as Eq. (6):

$$T_{SD} = \sum_{ij \in p} t_{ij} \leq T \tag{6}$$

2.3.2 Energy limitation

Node $j \in N_i$ must have enough energy to receive sent data from node i. Hence, energy consumption of this node to receive data has been sent from node i, should be less than its residual energy. This constraint can be formulated as Eq. (7):

$$t_{ij} \times Q_{ij} \leq E_{j\text{res}} \quad \forall\ (i,j) \in L \tag{7}$$

where Q_{ij} indicates the energy consumption in link (i, j) per time unit. Guerriero et al. 2009 proposed Eq. (8) to calculate Q_{ij} in which ρ is constant and equal for all nodes.

$$Q_{ij} = \rho \times f \tag{8}$$

Besides, node $i \in N_i$ must have enough energy to send data toward the neighbor nodes. So, the residual energy of this node should be sufficient to transmit data to node j. Equation (9), guarantee this constraint.

$$t_{ij} \times P_{ij}^{(t)} \leq E_{i\text{res}} \quad \forall\ (i,j) \in L \tag{9}$$

Based on mentioned objective functions and constraints, the mathematical model can be formulated as a bi-objective function problem, which is described in Sect. 2.4.

2.4 The mathematical model

Suppose that x_{ij} denotes the binary variable associated with the link $(i,j) \quad \forall\ (i,j) \in L$ and x_{ij} is one, if link i, j belongs to the selected route and zero otherwise. Also, assume that at time t, there are L different routes connect nodes S to node D.

The problem is to select the best route among L routes connecting node S to node D, regarding energy consumption and link reliability, which can be mathematically stated as a bi-objective model as follows:

$$\min z_1 = \sum_{(i,j) \in L} m_{ij}(t).x_{ij} \tag{10}$$

$$\max z_2 = \prod_{(i,j) \in L} r(i,j)^{x_{ij}} \tag{11}$$

Subject to :

$$x_{ij}.t_{ij}.Q_{ij} \leq E_{\text{res}} \quad \forall\ (i,j) \in L, j \neq D \tag{12}$$

$$x_{ij}.t_{ij} \times P_{ij}(t) \leq E_{\text{res}} \quad \forall\ (i,j) \in L, j \neq D \tag{13}$$

$$\sum_{\{j:(i,j) \in l\}} x_{ij} - \sum_{\{j:(j,i) \in l\}} x_{ji} = \begin{cases} 1 & \text{if } i = S \\ 0 & \text{if } i \in L - S, D \\ -1 & \text{if } i = D \end{cases} \tag{14}$$

$$\sum_{(i,j) \in p} t_{ij} x_{ij} \leq T \tag{15}$$

$$t_{ij} x_{ij} \leq R_i \quad \forall\ (i,j) \in L \tag{16}$$

$$x_{ij} \in \{0, 1\} \quad \forall\ (i,j) \in L \tag{17}$$

The first objective function attempts to minimize energy consumption and the second one tries to maximize reliability of the system. First two constraints are energy limitations. Equation (14) is flow conservation constraint. This constraint ensures that for an intermediate node, incoming flow should be equal to outgoing flow. Equation (15) is transferring time constraint and Eq. (16) ensures that a link exists between two nodes, if the receiver node be in the range of transmitter node. The binary variables are indicated in Eq. (17).

It should be noted that there is a conflict among two proposed objective functions. In fact, choosing a route with minimum energy consumption leads to a route with shorter links and the number of hops will be increased. On the other hand, maximizing reliability in a route needs fewer nodes regarding links loss probability. Hence, the mentioned conflict between these objective functions makes sense using proposed bi-objective model.

One of the most widely used methods to solve multi-objective optimization problems is transforming it into a single one. In this paper, the L_p-metric method is used to transform proposed bi-objective model to a single one. In this method the differences between the objective functions and their optimum values are minimized as shown in Eq. (18) (Stadler 1984; Ehrgott and Gandibleux 2002).

$$\text{Min } F(x) = \left[\sum_{i=1}^{Q} w_i \left| \frac{z_i^* - z_i(x)}{z_i^*} \right|^{\eta} \right]^{\frac{1}{\eta}} \tag{18}$$

where w_i is the weight of each objective function and i indicates the number of investigated objective functions. Indeed, this method tries to find optimum value of each objective function individually (z_i^*) and then, looks for an optimal solution that is closer to these point. The L_p-metric for $\eta = 1$ is called Manhattan metric, which is used in this research. Furthermore, with regard to equivalent worth of the objective functions in this paper, equal weight for them is considered $\left(w_1 = w_2 = \frac{1}{2}\right)$.

3 Numerical example

In this section, as a numerical example, a simple MANET is considered at time t in which 10 nodes are randomly placed on a given area (Fig. 3). (a, b) values on each link

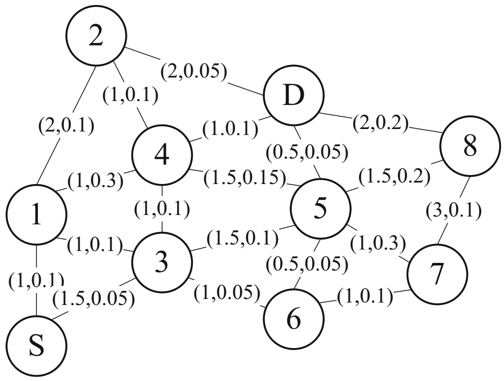

Fig. 3 Numerical example MANET

Table 1 Numerical example parameters

Parameter	Value
β	0.0000001 J/bm4
ρ	0.0001 J/b
n	4
f	10 Mbps
E_0	1 J

indicate the transferring time of that link and the failure rate of the link, respectively.

Suppose that node S and D are the source node and destination node, respectively. The problem is to find a route among these two nodes for transferring 10 Mbps data (f). The initial energy of mobile nodes are assumed to be 1 J (E_0) and it is assumed that residual energy for all nodes are identical so that desirability for all neighbors are the same. Table 1 denotes the required parameters.

To transform the proposed bi-objective model to a single objective one, a L_p-metric method ($\eta = 1$) is used so that the best solution for each objective function with considering mentioned constraints is calculated individually and then sum of the difference between these functions and their best response, is minimized using Eq. (18). To solve the transformed single objective function and constraints (12)–(17), LINGO 15.0 software is employed. Table 2 denotes the calculated results for this example based on LINGO software.

According to Table 2, the best solution with regarding the energy consumption metric is S-1-4-D, while solving the model with considering reliability metric leads to another solution (S-3-6-5-D). Combining two objective functions and transforming the bi-objective model to a single one, leads to route S-1-3-6-5-D, which differs from past two routes. This conclusion indicates that there is a conflict between two mentioned metrics and considering only one of them cannot lead to the optimal solution. Hence, a balance among these two metrics is required and this balance can be using L_p-metric method so that the solution considers these two opposite metrics, simultaneously. Furthermore, using L_p-metric method facilitates decision making process by allowing decision makers consider different weighs for each metric.

Table 2 Numerical example results

Considered objective function		Optimal route
Individually	Energy consumption	S-1-4-D
Individually	Reliability	S-3-6-5-D
L_p-metric	Energy consumption + reliability	S-1-3-6-5-D

4 Conclusions

In this paper, a new bi-objective mathematical model for MANET routing problem is developed in which consumed energy and reliability of selected route are taken into account, simultaneously. First criterion leads the model to select a route with less energy consumption and the later, ensures a reliable route with less loss rate. Furthermore, some energy constraints are considered and transferring time limitations are attended in the proposed model as some constraints, which make this model closer to the real world situations. To solve the proposed model, a L_p-metric method is used and a small numerical example is solved based on this method by LINGO. The results indicated that the proposed model can lead to more confident solutions, which are based on both energy consumption and reliability metric. Furthermore, using L_p-metric method permits decision makers to distinct among objective functions regarding weight of each function.

Finally, despite considering reliability of each link, there are criteria, which can be used in defining reliability such as, bandwidth limitation, velocity of the nodes, security considerations, etc. Therefore, this model can be extended in different ways with regarding these criteria. Furthermore, here for the sake of simplicity, simple and small size networks are considered. Proposing solution methods such as metaheuristic algorithms for the more complex problems can be another field to extend this study.

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