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Highlights

- The evaluation method of the performance reliability of the MANET is proposed.
- A mission fails if the transmission delay exceeds the residual path lifetime.
- The effect of interference is studied based on signal-to-interference ratio.
- The topology optimization problem of the MANET is solved by genetic algorithm.

Performance reliability evaluation for mobile ad hoc networks

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Abstract: The reliability of the mobile ad hoc network (MANET) is receiving increasing attention. Previous works are mainly focused on the connectivity reliability of the MANET; however, its performance reliability has not been considered. In the MANET, the paths connecting two nodes are prone to continuous changes due to the mobility of nodes, which can result in a huge uncertainty on the transmission performance. Thus it is necessary to research the evaluation method of the performance reliability of the MANET. In this study, the transmission reliability is defined to measure the reliability of the transmission performance of the MANET. The impact of interference on the transmission reliability is considered. The topology optimization of the MANET is studied based on the transmission reliability, and genetic algorithm is adopted to solve the optimization problem. In the numerical example, the effects of the involved parameters on the transmission reliability are discussed, and some applicable conditions of the optimal design are analyzed for practical applications.

Keywords: Mobile ad hoc network; Performance reliability; Interference; Transmission reliability; Genetic algorithm

1 Introduction

The mobile ad hoc network (MANET) is an emerging communication technology [1]. Its flexible and easy deployment has attracted different application areas, such as military [2], disaster recovery [3] and vehicular communication [4]. In simple terms, the MANET is an autonomous wireless network without fixed infrastructure, and it consists of nodes which can move dynamically [5]. A link (or called a hop) between two nodes exists if both nodes are in the communication range of each other. Multi-hop communication is popularly applied in the MANET to increase the overall network capacity and performance [6]. A multi-hop path connecting two nodes can be established by taking other nodes as relay nodes.

Network reliability refers to the probability that the function of a network can meet the use requirement, and it is an important index to weigh network performance [7]. Network reliability has been researched in many fields, such as communication [8], transportation [9] and electric power [10], to design new systems or improve existing systems. The connectivity reliability and the performance reliability are two branches of network reliability, and both of them are important for the reliability evaluation of networks [11]. The connectivity reliability mainly studies the topology structure of networks, and it is defined as the probability that a certain set of nodes in a network are connected [12]. The performance reliability is related to network performance, such as transmission delay for a communication network, and it is defined as the probability that the performance of a network can meet the use requirement [11].

Recently, the reliability of the MANET is receiving increasing attention. Most of the previous works are focused on the connectivity reliability. Such studies include Cook and Ramirez-Marquez [13-18], Padmavathy and Chaturvedi [19-21], Kharbash and Wang [22], Chen *et al*. [23], Wang [24], etc. However, for the MANET, it is untrue that a high connectivity reliability can guarantee an excellent transmission performance, and it is one-sided to evaluate the reliability by only considering the connectivity reliability [11]. In the MANET, the paths connecting two nodes are prone to continuous changes due to the mobility of nodes, which can result in a huge uncertainty on the transmission performance [25]. The connectivity reliability measures the ability of the MANET to maintain the connectivity of nodes. Two nodes are connected as long as there are paths between them. However, the connectivity reliability cannot reflect the effect of the change of paths on the transmission performance. If the paths connecting two nodes vary frequently, communication interruptions may often occur between the nodes, and the transmission performance may be unsatisfactory. Therefore, it is needed to consider the performance reliability of the MANET.

Performance metrics, such as transmission delay [26], throughput [27], outage probability [28], packet loss probability [29] and packet reception ratio [30], have been studied for the MANET in the literature. However, none of them can sufficiently measure the ability of the transmission performance of the MANET to meet the use requirement. In this study, the reliability of the transmission performance of the MANET is investigated by considering the effect of interference. Interference usually causes the degradation of the communication quality of the MANET, thus it is essential to evaluate its effect on the transmission performance [31]. Interference occurs when a transmitter node is transmitting to a receiver node, and meanwhile at least one additional node in the interference range of the receiver node is transmitting at the same frequency channel [32,33]. Moreover, we consider the use requirement as that a mission with several packets to transmit between a transmitter-receiver pair of nodes is needed to be accomplished within the available duration. Formally, we define the transmission reliability as the probability that the transmission delay of a mission between a transmitter-receiver pair of nodes does not exceed the available duration for the mission. Furthermore, the topology optimization of the MANET is studied based on the transmission reliability, and genetic algorithm (GA) is adopted to solve the optimization problem.

The remainder of the paper is organized as follows. In Section 2, the modeling assumptions, including the network model, the mobility model, the transmission scheme and the interference model, are described in detail. In Section 3, the evaluation method of the performance reliability is provided. In Section 4, the topology optimization of the MANET is considered. In Section 5, a numerical example is used to discuss the properties of the transmission reliability and the optimal design. Finally, some conclusions are summarized in Section 6.

2 Modeling assumptions

The main modeling assumptions are presented in this section. The research objective and the composition of the MANET are specified by the network model. The mobility pattern of nodes is described by the mobility model. Moreover, the communication in the MANET is determined by the transmission scheme and the interference model.

2.1 Network model

We consider a mission with m packets to transmit between a transmitter-receiver pair of nodes from the instant when a path connecting the two nodes is established. The transmitter and receiver are denoted by node s and node d, respectively. Nodes s and d can be two arbitrary nodes that are connected. Also, node d can be a base station collecting information from the other nodes, and node s is an arbitrary node that has a path with node d.

The network area is a square field of size L where total N nodes are distributed. Each node has the same symmetrical communication range R, and a link between two arbitrary nodes exists if the distance between them does not exceed R. The network area is assumed to be large enough so that $0 < R < L$ holds. Any node except nodes s and d can be used as a relay node. A path connecting nodes s and d can consist of at most a links. Here a is the maximum hop count. Equivalently, the communication between nodes s and d can utilize at most $a-1$ relay nodes.

2.2 Mobility model

All the nodes move within the network area according to the random direction mobility model with constant velocity. The random direction mobility model is a well-known model for the MANET [5,25,34,35]. At the beginning of the simulation, all the nodes are uniformly distributed in the region, and then each node selects a random direction in interval $\left[0, 2\pi\right)$ to move with a specified constant velocity. Once a mobile node reaches the boundary of the region, it selects a new direction in interval $\left[0, \pi\right]$ and continues moving with the specified velocity, and so on [25]. The direction is limited because the nodes do not pass through the boundary when they reach the boundary [35]. A useful property of the random direction mobility model is that the model can maintain the uniform spatial distribution of nodes during the simulation time [34].

2.3 Transmission scheme

The routing protocol is assumed to be in a single-path and on-demand fashion, which is often used in practical applications [36]. A path found by the routing protocol follows the shortest path, and the length of a path is the number of links forming the path [27].

Carrier sense multiple access with collision avoidance (CSMA/CA) is employed as the medium access control (MAC) protocol [37]. When a path connecting nodes *s* and *d* is established, a reservation time is set for performing a mission. Within the duration of the reservation time, the other nodes do not communicate with node *s*, node *d* and their relay nodes owing to the use of CSMA/CA. The risk of collisions is thereby avoided. Node *s* sends packets one by one to node *d*. Once a packet is received by node *d* successfully, node *s* sends the next packet immediately. An acknowledgment (ACK) message is used to verify a successful transmission between nodes *s* and *d*. When node *d* receives a packet successfully, it sends an ACK back to node *s*. For simplicity, we assume that the transmission duration of an ACK is negligible due to its very short length. Consider that an *i*-hop path is established between nodes *s* and *d*, and let Δt be the transmission duration of a packet through a single link. If node *s* does not receive an ACK after duration $i\Delta t$ since the time when it sends a packet, it attempts to retransmit the packet immediately. Retransmission attempt is executed every other duration $i\Delta t$ until node *s* receives an ACK.

At any time point, only a single link within the path connecting nodes *s* and *d* is active in transmitting a packet. We define that the current transmitter and the current receiver are the two nodes which are attempting to transmit and receive a packet, respectively, through the current active link. A graphical explanation of the current transmitter and the current receiver is given in Fig. 1, where nodes *s* and *d* establish a 2-hop path by taking node *r* as a relay node. At time t_1, node *s* is attempting to transmit a packet to node *r*, thus nodes *s* and *r* are the current transmitter and the current receiver, respectively. At time $t_2\left(t_2 > t_1\right)$, node *r* has received the packet successfully, and is attempting to relay the packet to node *d*. Thus nodes *r* and *d* are the current transmitter and the current receiver, respectively, at time t_2.

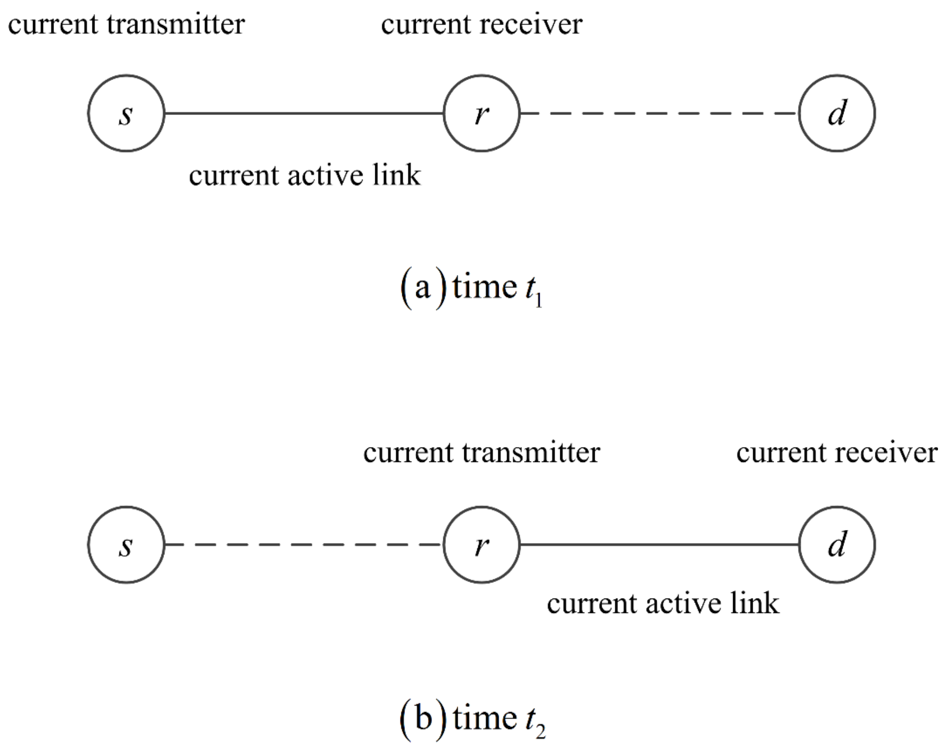

Fig. 1. Graphical explanation of the current transmitter and the current receiver.

2.4 Interference model

We assume that all the nodes in the network area share the same frequency channel. All the nodes except node *s*, node *d* and their relay nodes are considered as interferers. The interference range is assumed to be the same as the communication range. Interference occurs when the current transmitter is transmitting, and meanwhile at least one interferer in the interference range of the current receiver is also transmitting. The interferers which actually cause interference are referred to as active interferers. We assume that at any time point an interferer is transmitting with transmission probability *p*. Thus when the current transmitter is transmitting, an interferer in the interference range of the current receiver is an active interferer with probability *p*.

The channel is modeled by assuming distance-dependent path loss without fading [38,39]. If a node is transmitting in the interference range of the current receiver, the signal power received by the current receiver is given by

$$I = P_{tra} l\left(D\right) \tag{1}$$

where P_{tra} is the transmitting power, D is the distance between the two nodes, and $l\left(D\right)$ is the path loss between the two nodes. A commonly used path loss model named the singular model is applied, and is expressed by

$$l\left(D\right) = D^{-\alpha} \tag{2}$$

where $\alpha > 2$ is the path loss exponent [33,38,40-42].

Signal-to-interference ratio (SIR) is a key measure of interference [32,33,38,43]. The SIR at the current receiver is calculated by

$$\mathrm{SIR} = I_{ct} / I_{agg} \tag{3}$$

where I_{ct} is the signal power from the current transmitter, and I_{agg} is the aggregate interference power. The aggregate interference power is the sum of all the interfering signal powers [39]. Then we have $I_{agg} = \sum_{v \in \Phi_{N_{int}}} I_v$, where $\Phi_{N_{int}}$ is the set of all the active interferers with total number N_{int}, and I_v is the signal power from node *v* which is an active interferer. If N_{int} is equal to zero, $\Phi_{N_{int}}$ is empty and I_{agg} is equal to zero.

It is assumed that a successful transmission between the current transmitter and the current receiver occurs, if and only if $\mathrm{SIR} \geq \theta$ is achieved at the current receiver [32]. Here θ is the receiver threshold.

3 Performance reliability evaluation

3.1 Residual path lifetime

For on-demand routing protocols, such as ad hoc on-demand distance vector (AODV), dynamic source routing (DSR) and destination sequenced distance vector (DSDV), the existence of a link between two nodes is inspected at random time points, and the residual link lifetime is of concern [25]. The residual link lifetime is defined as the time interval from the time when the link is established to the time when the link breaks [25]. Furthermore, the residual path lifetime is defined as the time interval from path establishment until one of the links forming the path is unavailable [25]. Under the assumption that the residual link lifetimes of individual links forming a path are mutually independent [25], the residual path lifetime of an *i*-hop path T_{rpl}^{i} is given by

$$T_{rpl}^{i} = \min_{j=1}^{i} \left\{ T_{rll}^{j} \right\} \tag{4}$$

where T_{rll}^{j} is the residual link lifetime of the *j*th link. Thus the cumulative distribution function (CDF) of T_{rpl}^{i} at time *t* is derived by

$$\begin{aligned} F_{T_{rpl}^{i}}(t) &= P\left(\min_{j=1}^{i} \left\{ T_{rll}^{j} \right\} \leq t \right) \\ &= 1 - P\left(T_{rll}^{1} > t, T_{rll}^{2} > t, \ldots, T_{rll}^{i} > t \right) \\ &= 1 - \left(\int_{t}^{\infty} f_{T_{rll}}(x)\, dx \right)^{i}, \quad t \geq 0 \end{aligned} \tag{5}$$

where $f_{T_{rll}}(x)$ is the probability density function (PDF) of the residual link lifetime at time *x*.

Based on the random direction mobility model with constant velocity, we adopt the analytical result presented in Ref [25] where $f_{T_{rll}}(x)$ is expressed by

$$f_{T_{rll}}(x) = \frac{1}{\pi^2 R^2 x}\left[4Rvx + 2(R - vx)(R + vx)\ln\left(\frac{R + vx}{|R - vx|}\right)\right], \quad x \ge 0 \tag{6}$$

where v is the constant velocity. The accuracy of Eq (6) has been proved by simulations [25]. Then Eq (5) can be specified as

$$F_{T_{rpl}^i}(t) = 1 - \left\{\int_t^{\infty} \frac{1}{\pi^2 R^2 x}\left[4Rvx + 2(R - vx)(R + vx)\ln\left(\frac{R + vx}{|R - vx|}\right)\right]dx\right\}^i, \quad t \ge 0. \tag{7}$$

3.2 Available duration for a mission

We consider that the available duration for a mission is the minimum value between the duration of the reservation time and the residual path lifetime of the chosen path. Then when an *i*-hop path between nodes *s* and *d* is established, the available duration T_{ad}^i is written as

$$T_{ad}^i = \min\left\{T_{rt}, T_{rpl}^i\right\} \tag{8}$$

where $T_{rt} > 0$ is the duration of the reservation time. Note that the duration of the reservation time is the upper bound of the available duration. Thus the range of values for T_{ad}^i is $[0, T_{rt}]$.

For $0 \le t < T_{rt}$, the CDF of T_{ad}^i at time *t*, denoted by $F_{T_{ad}^i}(t)$, is derived by

$$\begin{aligned} F_{T_{ad}^i}(t) &= P\left(\min\left\{T_{rt}, T_{rpl}^i\right\} \le t, 0 \le t < T_{rt}\right) \\ &= P\left(T_{rpl}^i \le t\right) \\ &= F_{T_{rpl}^i}(t), \quad 0 \le t < T_{rt}. \end{aligned} \tag{9}$$

For $t = T_{rt}$, we have

$$
\begin{aligned}
F_{T_{ad}^i}(t) &= P\left(\min\left\{T_{rt}, T_{rpl}^i\right\} \le t, t = T_{rt}\right) \\
&= P\left(\min\left\{T_{rt}, T_{rpl}^i\right\} \le T_{rt}\right) \\
&= 1, \quad t = T_{rt}.
\end{aligned}
\tag{10}
$$

Therefore, the CDF of T_{ad}^i at time *t* is finally given by

$$
F_{T_{ad}^i}(t) = \begin{cases} F_{T_{rpl}^i}(t), & 0 \le t < T_{rt} \\ 1, & t = T_{rt}. \end{cases}
\tag{11}
$$

3.3 Transmission delay of a mission

For an *i*-hop path, let P_{SIR}^{N-i-1} be the probability of a successful transmission between the current transmitter and the current receiver in one transmission attempt. Specifically, P_{SIR}^{N-i-1} is the probability of $\mathrm{SIR} \ge \theta$ with $N-i-1$ interferers. By assuming that each node has an identical transmitting power [39], from Eqs (1), (2) and (3), P_{SIR}^{N-i-1} can be expressed by

$$
\begin{aligned}
P_{SIR}^{N-i-1} &= P\left(\mathrm{SIR} \ge \theta\right) \\
&= P\left(\frac{\left(D_{ct}\right)^{-\alpha}}{\sum_{v\in\Phi_{N_{int}}} \left(D_v\right)^{-\alpha}} \ge \theta\right)
\end{aligned}
\tag{12}
$$

where D_{ct} is the distance between the current transmitter and the current receiver, and D_v is the distance between an active interferer and the current receiver. Monte Carlo simulation is adopted to calculate Eq (12), since no closed form can be obtained. The algorithm is explained later in Appendix A in detail.

A successful transmission of a packet between nodes *s* and *d* occurs, if the packet is transmitted successfully over all the links constructing the path. Thus for an *i*-hop path, $\left(P_{SIR}^{N-i-1}\right)^i$ is the probability of a successful transmission between nodes *s* and *d* in one transmission attempt.

Because the transmission duration of a packet through a single link is Δt, at least $i\Delta t$ is needed to achieve a successful transmission between nodes *s* and *d*. Then at least $mi\Delta t$ is needed for a mission with *m* packets. Thus for $0 \le t < mi\Delta t$, we have $P\left(T_{i-hop}^{m} \le t\right) = 0$, where T_{i-hop}^{m} is the transmission delay of a mission with *m* packets through an *i*-hop path.

Node *s* performs a transmission attempt every other $i\Delta t$. Then the maximum number of times of transmission attempts during *t* is $\left\lfloor t/\left(i\Delta t\right)\right\rfloor$, which is the greatest integer less than or equal to $t/\left(i\Delta t\right)$. Moreover, a mission fails if at most $m-1$ successful transmissions between nodes *s* and *d* occur during *t*. Thus for $t \ge mi\Delta t$, it is obtained that

$$\begin{aligned} P\left(T_{i-hop}^{m} \le t\right) &= P\left(N_{i-hop}^{m} \le \left\lfloor t/\left(i\Delta t\right)\right\rfloor\right) \\ &= 1 - P\left(N_{i-hop}^{m} > \left\lfloor t/\left(i\Delta t\right)\right\rfloor\right) \\ &= 1 - \sum_{j=0}^{m-1} \binom{\left\lfloor t/\left(i\Delta t\right)\right\rfloor}{j} \left[\left(P_{SIR}^{N-i-1}\right)^{i}\right]^{j} \left[1-\left(P_{SIR}^{N-i-1}\right)^{i}\right]^{\left\lfloor t/\left(i\Delta t\right)\right\rfloor - j}, \quad t \ge mi\Delta t \end{aligned} \tag{13}$$

where N_{i-hop}^{m} is the number of times of transmission attempts needed to accomplish the mission.

Therefore, the CDF of T_{i-hop}^{m} at time *t* is given by

$$F_{T_{i-hop}^{m}}\left(t\right) = \begin{cases} 0, & 0 \le t < mi\Delta t \\ 1 - \sum_{j=0}^{m-1} \binom{\left\lfloor t/\left(i\Delta t\right)\right\rfloor}{j} \left[\left(P_{SIR}^{N-i-1}\right)^{i}\right]^{j} \left[1-\left(P_{SIR}^{N-i-1}\right)^{i}\right]^{\left\lfloor t/\left(i\Delta t\right)\right\rfloor - j}, & t \ge mi\Delta t. \end{cases} \tag{14}$$

3.4 Probability of a successful mission

A successful mission occurs if the transmission delay does not exceed the available duration. Thus the probability of a successful mission with *m* packets through an *i*-hop path, denoted by P_{mis}^{i}, is derived by

$$\begin{aligned} P_{mis}^{i} &= P\left(T_{i-hop}^{m} \le T_{ad}^{i}\right) \\ &= \int_{0}^{T_{rt}} P\left(T_{i-hop}^{m} \le t\right) f_{T_{ad}^{i}}\left(t\right) dt \\ &= \int_{0}^{T_{rt}} F_{T_{i-hop}^{m}}\left(t\right) f_{T_{ad}^{i}}\left(t\right) dt \end{aligned} \tag{15}$$

where $f_{T_{ad}^{i}}\left(t\right)$ is the PDF of T_{ad}^{i} at time *t*. No closed form can be obtained for Eq (15), thus the evaluation problem is solved numerically using MATLAB. Specifically, Eq (15) is approximated by

$$P_{mis}^{i} = \sum_{j=1}^{N_F} F_{T_{i-hop}^{m}}\left(t_j\right) \Big/ N_F \tag{16}$$

where t_j is a sample of the available duration from distribution $F_{T_{ad}^{i}}$ given by Eq (11), and N_F is the total number of samples. t_j is generated by the following two steps.

Step 1. Generate a random number *u* from the uniform distribution $U\left(0,1\right)$.

Step 2. If $u \le F_{T_{rpl}^{i}}\left(T_{rt}\right)$, solve equation $F_{T_{rpl}^{i}}\left(t_j\right) = u$ by routine “fsolve”. Otherwise, if $u > F_{T_{rpl}^{i}}\left(T_{rt}\right)$, set $t_j = T_{rt}$.

3.5 Transmission reliability

Considering a mission with *m* packets and paths with at most *a* links, we define the transmission reliability as the probability that the transmission delay of the mission between a transmitter-receiver pair of nodes does not exceed the available duration for the mission. Then the transmission reliability R_{a-hop}^{m} is given by

$$R_{a-hop}^{m} = \sum_{i=1}^{a} P_{a-hop}^{i} P_{mis}^{i} \tag{17}$$

where P_{a-hop}^{i} is the probability that an *i*-hop path is chosen when the transmitter-receiver pair of nodes are connected by paths with at most *a* links. P_{a-hop}^{i} is calculated by

$$P_{a-hop}^{i} = \frac{P\left(\bigcap_{j=1}^{i-1}\bar{A}_j \bigcap A_i\right)}{P\left(\bigcup_{i=1}^{a}\left(\bigcap_{j=1}^{i-1}\bar{A}_j \bigcap A_i\right)\right)} = \frac{P(A_i)\prod_{j=1}^{i-1}\left(1-P\left(A_j\right)\right)}{\sum_{i=1}^{a}\left[P(A_i)\prod_{j=1}^{i-1}\left(1-P\left(A_j\right)\right)\right]} \tag{18}$$

where A_j is the event that there are *j*-hop paths between the transmitter-receiver pair of nodes, and $\bar{A}_j$ is the complementary event. In additional, we set $\prod_{j=1}^{i-1}\left(1-P\left(A_j\right)\right)=1$ for $i=1$. The calculation of $P\left(A_j\right)$ is explained in Appendix B.

4 Topology optimization

The topology optimization of the MANET is an important problem to efficiently use available resources to satisfy certain properties [34]. The topology of the MANET at any time point is defined by the size of the network area, the spatial distribution of nodes, the communication range and the number of nodes. The size of the network area and the spatial distribution of nodes are uncontrollable. The size of the network area cannot be adjusted arbitrarily, because it is a natural characteristic of the geographical environment chosen to execute missions such as rescue, surveillance and reconnaissance. Nodes are deployed in the network area following the uniform distribution due to the assumption of the random direction mobility model. Thus the spatial distribution of nodes is determined by the size of the network area. However, the communication range and the number of nodes are controllable variables. The communication range can be adjusted by changing the transmitting power, and the number of nodes can be allocated according to the requirement of missions. Therefore, we consider the communication range and the number of nodes as the decision variables of the topology optimization problem.

Based on the transmission reliability, the optimization problem is constructed as

$$\min \quad -R_{a-hop}^{m} \tag{19}$$

s.t.

$$\begin{cases} 0 < R \le U_R \\ L_N \le N \le U_N . \end{cases} \tag{20}$$

U_R is the upper bound of the communication range, which is determined by the communication capability of the equipped communication device. L_N is the lower bound of the number of nodes needed to perform missions in the network area. U_N is the upper bound of the number of nodes, and it is limited by the available resources.

Since the aforementioned optimization problem is complicated, GA is adopted to search the optimal design of the MANET. GA is a popular method to solve engineering optimization problems, because it can be used to a wide range of optimization problems, easily handle constrained optimization problems, and rapidly generate high-quality solutions [44].

5 Numerical example

A military scenario is considered based on the modeling assumptions described in Section 2. A group of soldiers with total *N* members are performing reconnaissance missions on a square battlefield of size *L*. Each soldier is equipped with an identical portable radio device with communication range *R*. Thus a MANET can be formed by taking each soldier as a network node. At a time point, soldiers A and B establish a path between them by utilizing at most *a* links, and soldier A attempts to fulfill a mission with *m* packets to transmit to soldier B. The *m* packets are the latest information collected from the battlefield. Parameter settings are presented in Table 1.

Table 1 Parameter settings for the MANET.

Parameter	Setting
Size of the battlefield *L*	1000 meters

Velocity of each soldier v	1.5 m/s
Transmission duration of a packet through a single link Δt	0.01 second
Duration of the reservation time T_{rt}	10 seconds
Transmission probability p	0.5
Number of packets m	5
Path loss exponent α	3
Receiver threshold θ	1

5.1 Sensitivity analysis

The effects of the number of soldiers and the communication range on the transmission reliability are investigated under different maximum hop counts, as shown in Figs 2 and 3, respectively. The communication range is set to 200 meters in Fig. 2, and the number of soldiers is set to 10 in Fig. 3.

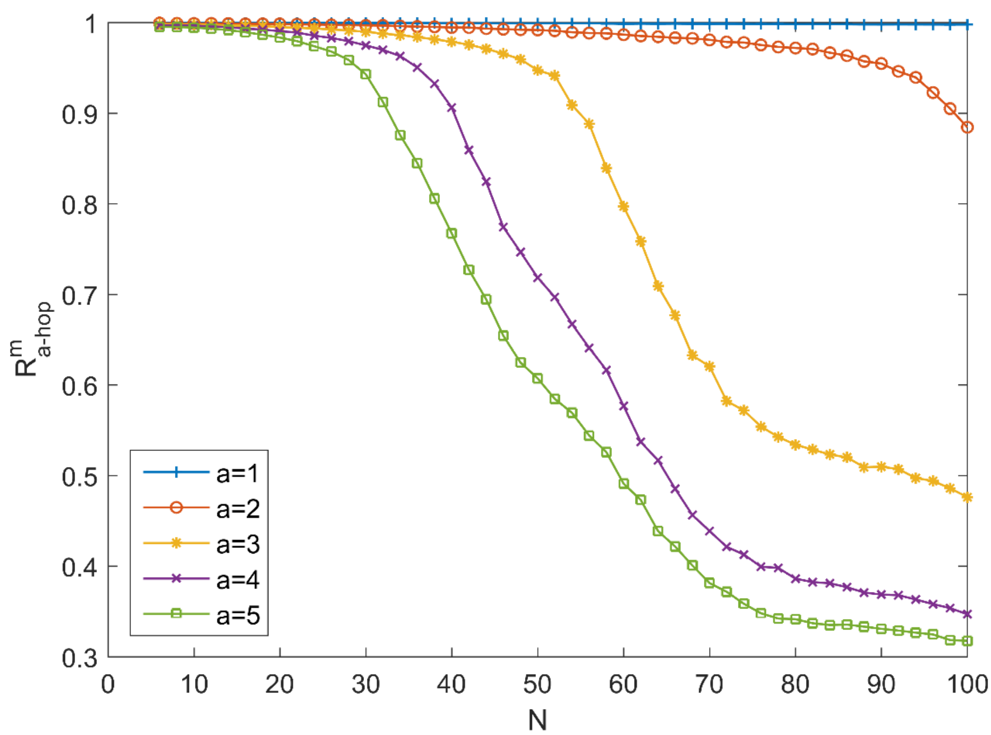

Fig. 2. The effect of the number of soldiers on the transmission reliability.

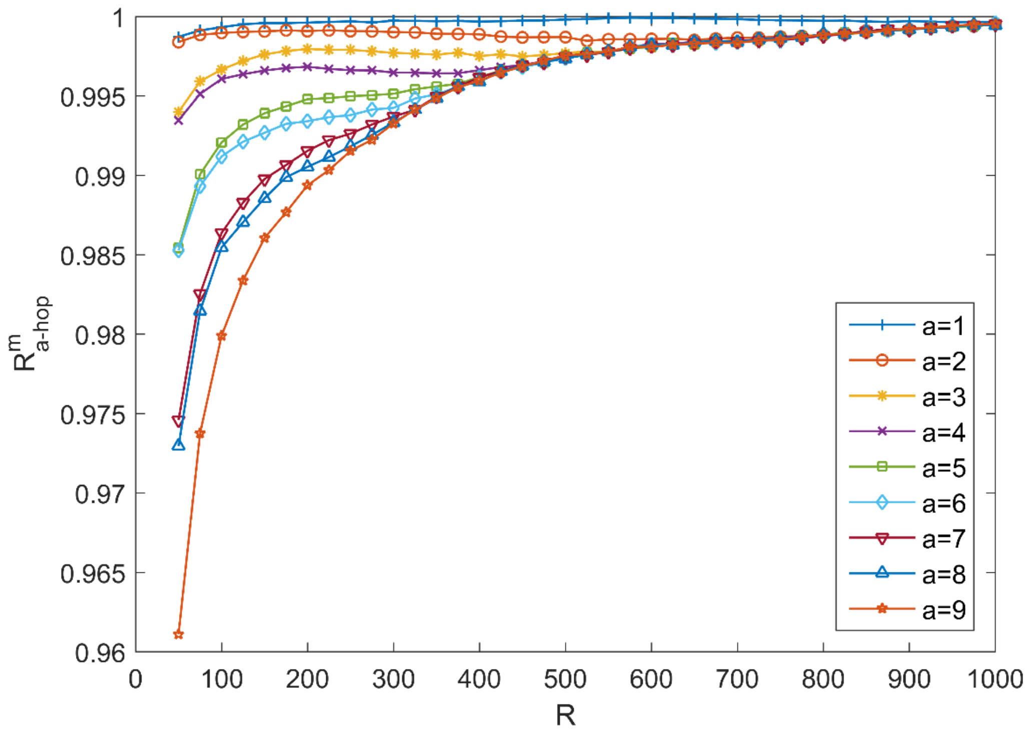

Fig. 3. The effect of the communication range on the transmission reliability.

From Fig. 2, the transmission reliability is monotonically decreasing with the increasing of the number of soldiers. To explain the effect of the number of soldiers on the transmission reliability, we first define $DN = \bar{D}/\bar{N}_{hop}$, where $\bar{D}$ and $\bar{N}_{hop}$ are the average communication distance and the average used hop count, respectively, between soldiers A and B. If the value of DN is equal to the communication range, the chosen path between soldiers A and B is a straight line, and each relay soldier is located at the edge of the communication range of its neighboring soldiers in the path. The respective calculation methods of $\bar{N}_{hop}$ and $\bar{D}$ are presented as follows. The used hop count N_{hop} follows the distribution given by $P\left(N_{hop} = i\right) = P^i_{a-hop}, i = 1, 2, ..., a$, thus $\bar{N}_{hop}$ is calculated by $\sum_{i=1}^{a} iP^i_{a-hop}$. $\bar{D}$ is approximated by Monte Carlo simulation. In each trial, we generate horizontal and vertical coordinates of all the soldiers from the uniform distribution $U(0, L)$. If soldiers A and B are connected by paths with at most *a* links, the distance between them is calculated. The method of checking the connectivity between two soldiers is explained in Appendix B. An approximation of $\bar{D}$ is given by averaging the distances collected from the simulations where soldiers A and B are connected by paths with at most *a* links. Then the effect of the number of soldiers on *DN* is presented in Fig. 4, where the communication range is assumed to be 200 meters.

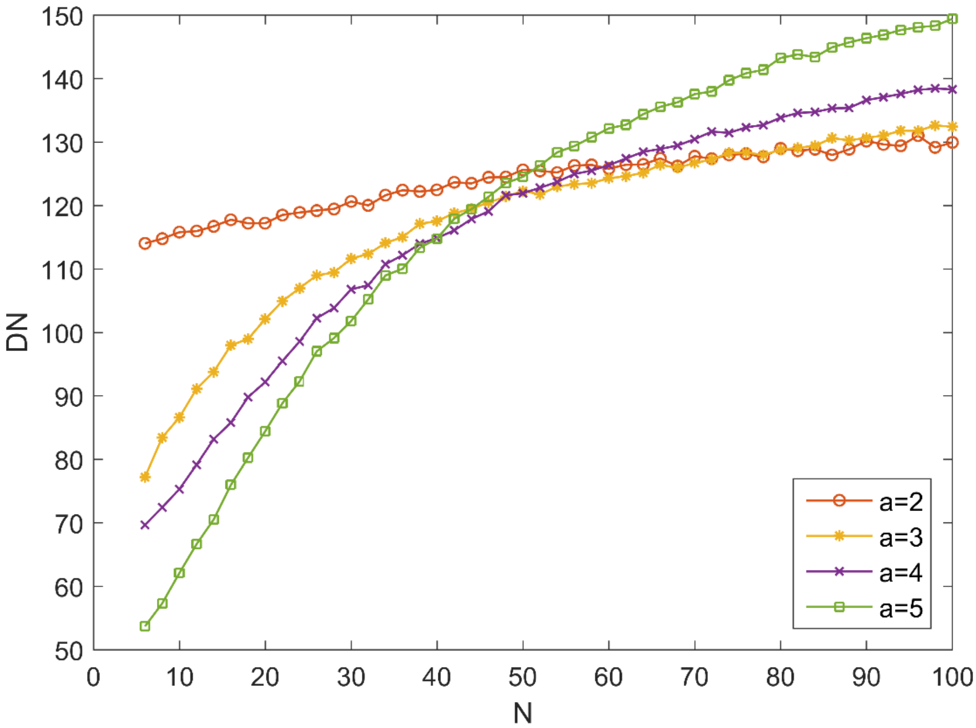

Fig. 4. The effect of the number of soldiers on *DN*.

From Fig. 4, the value of *DN* approaches the communication range with the increasing of the number of soldiers. This indicates that as the number of soldiers increases, the chosen path between soldiers A and B tends to be a straight line, and each relay soldier tends to be located at the edge of the communication range of its neighboring soldiers in the path. Lim *et al*. [45] named the phenomenon as edge effect. Due to the edge effect, the residual path lifetime could decrease with the increasing of the number of soldiers [45], and hence the available duration for a mission may also decrease. Furthermore, as the number of soldiers increases, the impact of interference becomes increasingly serious, which could lead to a longer transmission delay. Both the reduction of the available duration and the growth of the transmission delay could decrease the transmission reliability. Therefore, the transmission reliability is a monotonically decreasing function of the number of soldiers.

The effect of the communication range on the transmission reliability is relatively complex. Consider the situation that a small communication range is used. On the one hand, the possibility that an interferer is in the interference range is low, so that there could be few active interferers, which is beneficial to the transmission reliability. On the other hand, the residual path lifetime could be short, and hence the available duration for a mission could also be short, which is harmful to the transmission reliability. For a large communication range, the impact of interference could be terrible, resulting in a long transmission delay. At the same time, the residual path lifetime could also be long, thus a long available duration for a mission may be achieved.

Although it is difficult to explain the effect of the communication range on the transmission reliability, it is evident that the transmission reliability is greatly affected by the communication range as shown in Fig. 3. There exists a critical maximum hop count, which is equal to 5 in this example. If the used maximum hop count is less than the critical maximum hop count, the transmission reliability is a non-monotonic function of the communication range. However, if the used maximum hop count is no less than the critical maximum hop count, the transmission reliability transforms into a monotonically increasing function of the communication range.

5.2 Optimal design

The topology optimization of the MANET is considered under different maximum hop counts, based on the framework constructed in Section 4. The average used hop count and the average communication distance between soldiers A and B are also investigated. It is assumed that $U_R = 300$ meters, $L_N = 10$ and $U_N = 100$. The computational results are shown in Table 2, where N^* and R^* are the optimal number of soldiers and the optimal communication range, respectively.

Table 2 Optimal designs of the MANET under different maximum hop counts.

a	N^*	R^*	$\bar{N}_{hop}$	$\bar{D}$	R^m_{a-hop}
1	10	300	1	192.4	0.9998
2	10	173.2	1.338	134.6	0.9993
3	10	221.8	2.012	202.2	0.9981
4	10	202.4	2.381	182.9	0.9970
5	10	300	2.626	330.6	0.9950
6	10	300	2.831	331.7	0.9944
7	10	300	2.998	332.6	0.9936
8	10	300	3.104	333.7	0.9933
9	10	300	3.181	334.4	0.9928

The optimal number of soldiers is at the lower bound, because the transmission reliability is a monotonically decreasing function of the number of soldiers. For the cases with $a \geq 5$, the optimal communication range is at the upper bound, because in these cases the transmission reliability increases with the increasing of the communication range. For the case with $a = 1$ and the cases with $a \geq 5$, the lifetimes of the portable radio devices may be shorter than the lifetimes of the devices in other cases, because they have larger optimal communication ranges. The devices are powered by batteries with limited energy, and a larger communication range is achieved by more energy consumption [46].

As the maximum hop count increases, more relay nodes can be used to construct paths, so that the average used hop count increases. Consequently, it is intuitive that the average communication distance may also increase. However, it is observed from Table 2 that the average communication distance is not monotonically increasing with the growth of the maximum hop count. This is because the optimal communication ranges of the cases with $a = 2,3,4$ are different from the optimal communication ranges of the other cases.

The use of multiple hops is beneficial to the realization of long-distance communication. However, Table 2 indicates that the growth of the maximum hop count can decrease the maximum achievable transmission reliability. This is because for a path constructed by more hops, the transmission delay could be longer. However, the residual path lifetime could be shorter [47], so that the available duration for a mission could also be shorter. Thus using over many hops is not suggested in practice.

Therefore, different deployments of the MANET can be set by the designer under different considerations.

(1) If the most energy-saving deployment is required due to a long duration of missions, the optimal design with the shortest optimal communication range is suggested.

(2) If the maximization of the transmission reliability is taken as the design criterion, the optimal design with only single-hop communication is preferred.

(3) If long-distance communication is necessary for missions, the designer can consider the optimal design with the greatest maximum hop count which can be achieved by the available technology.

6 Conclusions

This study considers the performance reliability of the MANET. The transmission reliability is defined to measure the reliability of the transmission performance of the MANET. The evaluation method is provided based on the assumptions of the random direction mobility model with constant velocity, a single-path and on-demand routing protocol, the CSMA/CA protocol and the singular path loss model. Taking the number of nodes and the communication range as the decision variables, the topology optimization problem of the MANET is solved by GA. It is revealed that the transmission reliability is a monotonically decreasing function of the number of nodes. There exists a critical maximum hop count. If the used maximum hop count is less than the critical maximum hop count, the transmission reliability is a non-monotonic function of the communication range. However, if the used maximum hop count is no less than the critical maximum hop count, the transmission reliability is a monotonically increasing function of the communication range. Using over many hops is not suggested in practice, because the growth of the maximum hop count can decrease the maximum achievable transmission reliability. Moreover, different deployments of the MANET have been discussed in detail under different considerations for practical applications.

From the macroscopic point of view, the transmission reliability is used as a performance reliability index for the overall transmission performance of the MANET, and does not describe the effect of the locations of nodes at a specific time point. Thus, on the micro level, time dependent reliability indices and location dependent reliability indices can be investigated in the future research.

Appendix

A. Calculation of P_{SIR}^{N-i-1}

First, the respective distributions of N_{int}, D_{ct} and D_v are derived as follows.

Let P_{in} be the probability that two nodes are in the communication range of each other. Considering two arbitrary nodes, their horizontal and vertical coordinates both follow the uniform distribution $U(0,L)$. Let ΔX and ΔY be the absolute values of the relative horizontal coordinate and the relative vertical coordinate, respectively. Then we have

$$\begin{cases} f_{\Delta X}(\Delta x) = 2/L - 2\Delta x/L^2, & 0 \le \Delta x \le L \\ f_{\Delta Y}(\Delta y) = 2/L - 2\Delta y/L^2, & 0 \le \Delta y \le L \end{cases} \tag{A.1}$$

where $f_{\Delta X}$ and $f_{\Delta Y}$ are the PDFs of ΔX and ΔY, respectively. Thus considering $0 < R < L$, P_{in} is derived by

$$\begin{aligned} P_{in} &= P\left(\sqrt{(\Delta X)^2 + (\Delta Y)^2} \le R\right) \\ &= \int_0^R \int_0^{\sqrt{R^2-(\Delta y)^2}} \left(2/L - 2\Delta x/L^2\right)\left(2/L - 2\Delta y/L^2\right) d\Delta x d\Delta y \\ &= \pi R^2/L^2 - 8R^3/\left(3L^3\right) + R^4/\left(2L^4\right). \end{aligned} \tag{A.2}$$

When the current transmitter is transmitting, pP_{in} is the probability that an interferer is also transmitting and is in the interference range of the current receiver. Thus for an *i*-hop path, N_{int} follows the binomial distribution

$$P(N_{int} = n) = \binom{N-i-1}{n}(1 - pP_{in})^{N-i-1-n}(pP_{in})^n, \quad n = 0,1,...,N-i-1. \tag{A.3}$$

For D_{ct} and D_v, they have the same PDF, which is given by

$$f_D(d) = 2d/R^2, \quad 0 \le d \le R \tag{A.4}$$

because if a node is in the communication range of the current receiver, the node is uniformly distributed over the range [25].

Then, the calculation algorithm of P_{SIR}^{N-i-1} is given as follows.

Step 1. Initialize $N_{SIR} = 0$, where N_{SIR} is the number of times that $\text{SIR} \ge \theta$ is achieved.

Step 2. Generate N_{int} from Eq (A.3). If $N_{int} = 0$, set $N_{SIR} = N_{SIR} + 1$, then go to Step 5. Otherwise, go to Step 3.

Step 3. Generate D_{ct} and $D_v, v = 1,2,...,N_{int}$ from Eq (A.4).

Step 4. Calculate $\text{SIR} = (D_{ct})^{-\alpha} \Big/ \sum_{v=1}^{N_{int}} (D_v)^{-\alpha}$. If $\text{SIR} \ge \theta$, set $N_{SIR} = N_{SIR} + 1$.

Step 5. Repeat Steps 2-4 for N_{sim}^{SIR} times.

Step 6. Calculate $P_{SIR}^{N-i-1} = N_{SIR} / N_{sim}^{SIR}$.

B. Calculation of $P(A_j)$

$P(A_j)$ is unaffected by time, because the nodes are uniformly distributed in the network area at any time point. At a time point, the MANET can be represented by an adjacency matrix $Q = (q_{k,l})_{N \times N}$, which is defined by

$$q_{k,l} = \begin{cases} 1, & \text{if a link exists between the } k\text{th and } l\text{th nodes} \\ 0, & \text{else.} \end{cases} \tag{B.1}$$

The diagonal entries of *Q* are all set to zero. From Ray [48], the *k,l*-th entry of Q^j is the number of different *j*-hop paths between the *k*th and *l*th nodes. Here the *k,l*-th entry is the entry at the *k*th row and the *l*th column. Without loss of generality, we consider nodes *s* and *d* as the first and second nodes, respectively. Thus there are *j*-hop paths between nodes *s* and *d* if the *1,2*-th entry of Q^j is non-zero. Moreover, nodes *s* and *d* are connected by paths with at most *a* links if the *1,2*-th entry of $\sum_{j=1}^{a} Q^j$ is non-zero.

For $j = 1$, the analytical result of $P(A_1)$ can be obtained by Eq (A.2). However, for the other cases, there is no closed form thus Monte Carlo simulation is used. The calculation algorithm of $P(A_j)$ is given as follows.

Step 1. Initialize $N_{j-hop} = 0$, where N_{j-hop} is the number of times that there are *j*-hop paths between nodes *s* and *d*.

Step 2. Generate horizontal and vertical coordinates for all the *N* nodes from the uniform distribution $U(0, L)$.

Step 3. Calculate the distance of each pair of nodes by $\sqrt{(\Delta X)^2 + (\Delta Y)^2}$.

Step 4. A link between two nodes exists if their distance does not exceed *R*. Then renew *Q* according to Eq (B.1).

Step 5. Calculate Q^j. If the *1,2*-th entry of Q^j is non-zero, set $N_{j-hop} = N_{j-hop} + 1$.

Step 6. Repeat Steps 2-5 for N_{sim}^{j-hop} times.

Step 7. Calculate $P(A_j) = N_{j-hop} / N_{sim}^{j-hop}$.

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