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Dynamic Analysis for the Average Shortest Path Length of Mobile Ad Hoc Networks Under Random Failure Scenarios

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ABSTRACT In general, the mobile ad hoc networks (MANETs) are built on the basis of the random distribution of the nodes, while the nodes of real networks usually have the characteristics of location preference choice. The evolving network model based on local-area choice is proposed for MANET based on the complex network theory. The proposed model of the topology not only considers the scale-free nature of the network and the actual mobility of MANET but also considers the consumption of the node energy. Random failures often occur in MANET. Most of the existing research focuses on the changes in network topology caused by random node failures. In order to describe the impact of random edge failures on the topology of MANET, we focus on the average shortest path length (ASPL) which is an important feature of the network topology and propose the formula for calculating the ASPL of the MANET after the random edge failure. The experimental simulation analyzes the change of the ASPL of MANET in the random failure scenario (after random edge deletion). By comparing with the actual scene results, the proposed estimation formula which describes this change more accurately is proved. The formula proposed in this paper provides a general framework for studying the shortest path of MANET.

INDEX TERMS ASPL, local-area choice, random edge failure, complex network, random failure, MANET.

I. INTRODUCTION

The MANET is a non-fixed topology network whose topology changes with the increase, decrease and movement of the nodes in the network [1]. Among the research of MANET, the research on the characteristics of network topology is the bridge and foundation for understanding other key technologies of the network. Therefore, we focus on the dynamic changes of MANET topology. In essence, the MANET is a complex network. We can find the solution to its specific problems through the theory of complex networks. When analyzing the nature of a particular MANET, the theory of complex networks is equally applicable to MANET.

Nowadays more and more studies have shown that human society is full of various complex structural relationships [2]. Such as networks, transportation networks, power networks, research cooperation networks, social networks, metabolic networks, infectious disease transmission networks, etc.; although these networks stay in different scientific fields, they have common characteristics; such complex networks are collectively called Complex network [3]. The theory of studying the characteristics and processing methods of these complex networks is called complex network theory [3]. Qian XueSen has given a more rigorous definition of complex networks: networks with self-organization, self-similarity,

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attractors, small worlds, and some or all of the scale-free nature is called complex networks, referred to as highly complex networks [4].

The key technologies for studying complex networks are: routing protocols, evolution models of network topologies, community structures, and damage resistance. At this point, the evolutionary model of complex network topologies is the condition and basis for various key researches. According to the graph theory analysis, the nodes and the connecting edges of the network, and at the same time, constitute our common information network. The node can be a host, a client or a router, and the connection side can be divided into a wired link and a wireless transmission link. The host and the client can be combined into one class, called a terminal device. On the Internet, a large number of terminal devices are just placed at the end of the network. Therefore, the network linked by the router affects the information transmission of the network and the structure of the network. In addition, the network in which a single node is both a router and a terminal forms another network model, such as the MANET we studied. In such networks, a single node can generate data, receive data, and forward data. Figure 1 depicts the different node forms: the squares represent the terminals and the dots represent the routers.

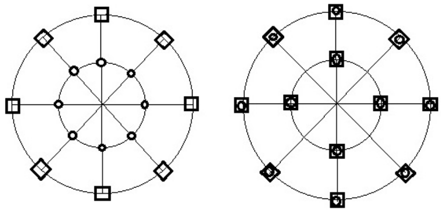


FIGURE 1. Different forms of nodes.

At the beginning of network research, scholars abstracted the topological structure of the network into a regular connection model. One of the most prominent characteristics of this model is that each node in the network has the same degree and its degree distribution obeys the δ function, namely:

$$P(k) = \begin{cases} 1, & k = m \\ 0, & k \neq m \end{cases} \tag{1}$$

This is called the theoretical concept of the rule network. Further study of the network structure shows that it is difficult to further describe the structure characteristics of the real network through regular network. In the mid-20th century, Hungarian scientists Paul Ordos and Erederenyi further explored their own research. A random network structure (usually called random network) was proposed, which is considered as a leap forward in the development of modern network theory [5].

Figure 2 depicts the evolution of the three network models. Although the regular networks are simple in structure, they are not necessarily limited to simple ring networks or square networks. In fact, there are some relatively complex rule networks, such as Bayesian rule networks. Their degree distributions obey the equation (1), but their clustering coefficient and average distance are quite different [6].

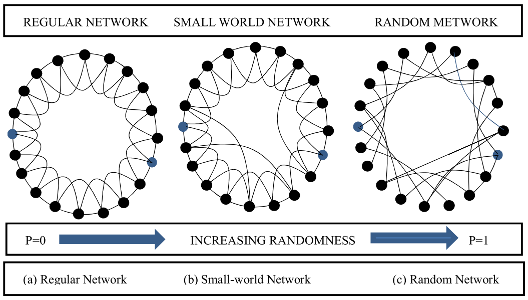


FIGURE 2. The evolution of three network models [7].

In Figure 2 (c), the process of constructing an ER random network is as follows: Set the total number of network nodes to N; for each time step, randomly select two nodes and connect them with probability $p = 2n/(N(N-1))$. The final total number of edges of the network is recorded as n, $n < N(N-1)/2$. When $n = N(N-1)/2$, the network stops evolving. The average of the established random networks is $p(N-1) \approx pN$. ER and Balabas give the degree distribution of random networks as follows:

$$P(k) = C_{N-1}^{k} p^{k} (1-p)^{N-k} \approx \frac{\langle k \rangle^{k} e^{-\langle k \rangle}}{k!} \tag{2}$$

In 1998, American physicists Watts and Strogatz proposed the small-world network model, a complex network model with such complex network characteristics. Because of the small average distance and the large clustering coefficient, the small-world network model has some characteristics of regular network and random network, and can also be a completely regular network transformed to a completely random network through the small-world model, as shown in Figure 2(b).

The in-depth study of the structural model of the network topology lays the foundation for the researches of complex networks. The topological model of the complex network can be used to describe the structural characteristics of many networks in reality and the laws of topological evolution. Therefore, the study of real network topology is mainly based on a complex network theory. As complex network theory has developed to such a stage nowadays, the detailed description of real networks becomes our research hotspot.

The thorough study of the structural characteristics of network topology is the basis for the complex network theory to describe the real network. We focus on the changes in the structural characteristics of the network topology when the network topology is destroyed (such as random failure; random failure is the failure of any node or edge with the same probability or random deletion of a certain proportion of nodes or edges). Firstly, the evolution model of network topology is constructed by complex network theory, and then the structural changes of network topology are studied when the model is destroyed. Specifically, this paper studies the change of the ASPL of MANET when random failures occur, that is, the change of an important characteristic of random network topology. Most previous studies focused on the impact of random node failures on network topology. In MANET, routing construction and data transmission are based on the shortest path length. After random edge failure, the change of ASPL is studied, which provides a theoretical basis for the construction and maintenance of network routing.

II. RELATED WORKS

In recent years, various research institutes have conducted in-depth research on MANET, and have made a series of achievements in routing protocols, network security and quality of service [9]–[13]. At present, the MANET can be used in rescue and disaster relief, military applications, commercial areas, sensor networks and other scenarios, and its ideas can also be applied in the network [14]. After proving that networks in many fields have scale-free characteristics, scholars have proposed various network topology models for the scale-free networks based on the BA scale-free network model. In recent years, researchers have studied MANET topology evolution model through complex network theory, and proposed a large number of network topology evolution models.

Li and others propose a local world network evolution process that can measure the topology of the Internet [15]. Reference [16] proposes a complex network evolution model, the growth mechanism of which combines the characteristics of random growth and preferential connectivity. Considering the dynamic interaction, Song and Wang [17] proposes a topological evolution model for coupled networks. The weighted network evolution model proposed in [18] and [19] can truly show the distribution characteristics of edge weight and node degree of the weighted network. Shi Dinghua discusses the construction of network model [20] from the degree and distribution of network.

At present, the premise of MANET topology research is that in the simulation scenarios, the network nodes are set randomly, and the nodes move randomly in the network. However, in practice, the nodes in the network are not always randomly distributed, that is, the density of nodes in the network is different. The difference of node density will lead to the change of the topological structure of MANET, and then affect the control and security of MANET and routing strategy.

In reality, nodes have a tendency to choose mobile to evolve into MANET networks. For this feature, we propose Evolving Network Model based on Local-Area Choice (ENM-LAC) of MANET. Under the premise of considering the energy consumption of the network, the evolution process of the network is described according to the selection and mobility characteristics of nodes. First, the network is initialized. Some nodes are first configured in the network scenario, which is the basis of network evolution. Then, new nodes are added. The node degree of the existing nodes in the scene is calculated. According to the node degree distribution, the nodes are selectively added to the denser region of the degree distribution. The network distribution is formed. Finally, the new node establishes the link edge. The newly added node, based on the remaining energy and node degree and link distance of the existing node in its own coverage, probabilistically connects the existing nodes, and gradually evolves the network topology. Simulation results show that the proposed topology model not only has scale-free characteristics, and reduces the connection probability of nodes with a high degree of node by considering the residual energy and link distance of the node, but also balances the load of nodes in data transmission. The proposed topology model not only considers the scale-free characteristics and mobility of MANET, but also balances the node energy consumption effectively through the probabilistic connection edges.

The application of complexity theory to MANET research mostly concerned the nature of the network with the addition and deletion of nodes, the deletion and establishment of edges. The change of network topology is less concerned. Xie *et al.* synthetically considered the relationship between network topology and geometric distance between nodes, and proposed a network evolution model which conforms to the characteristics of MANET network. Reference [22] proposes a network evolution mechanism, including node growth rate, deletion rate and deletion compensation factor [22] in the scenario where nodes can join and leave MANET networks at will. Nemeth and Vattay studied the characteristics of giant clusters in MANET networks. The size of giant clusters in the proposed network model was uniquely determined by the average number of neighbors. Document [24] presents a scene topology model for complex networks applied to MANET networks. This paper suggests that the connection of the network is non-collusive, but ignores whether the node location distribution is uniform [24]. Qin *et al.* [25] proposed an evolutionary mechanism based on the evolutionary characteristics of the BA network in the local-world environment for the nonlinear growth of the joined edges of new nodes.

Summarizing the previous research literature, it can be seen that most of the research focus on the ability of the network to maintain structural and functional integrity after random failures or intentional attacks. For example, scale-free networks exhibit the resistance to random faults, but are vulnerable to be attacked by nodes with intentional attacks; when a certain proportion of nodes are randomly deleted from a BA scale-free random network, the remaining nodes can communicate with each other in a high probability, and the ASPL between these nodes varies little. If you deliberately delete some larger degree nodes, the network is easily disconnected [26], [27]. Son *et al.* [28] studied the probability distribution function of the node betweenness change value of the remaining nodes after one node was deleted, and found that it is a power function. Duch and Arenas [29] have studied the influence of the random failure of nodes on the maximum node betweenness. Qi *et al.* [30] experimentally studied the effects of random faults of nodes on some characteristics of network topology, such as the change of ASPL, but lacked more in-depth analysis. It is also necessary to study the effect of random faults on the structure of MANET from the edge view, but there are few experimental studies on this aspect. We focus on the effects of random failures on the ASPL of an important feature of the topology of MANET networks.

III. MODELING AND ALGORITHM DESIGN PRINCIPLES

Based on the mobility of real MANET and the preferred characteristics for the choice of location of the node distribution, an ENM-LAC model is proposed. Based on this model, the MANET is built, and the formula of the ASPL of the network after the network suffers from random edge failure is calculated.

A. THE EVOLVING NETWORK MODEL BASED ON LOCAL-AREA CHOICE

It is theoretically feasible to study the topology evolution of MANET by using complex network theory [31]. Applying the complex network theory to the topology control of MANET makes the topology of MANET have more characteristics, such as uneven distribution of nodes, balanced utilization of node energy, shortened link length and so on.

The self-organization of MANET reflects the characteristics of complex networks. A large number of studies show that the MANET is a communication network with the characteristics of scale-free network [32]. However, compared with the traditional communication network, it also has its own unique attributes, such as limitations on node transmission power, reception threshold, energy level, channel conditions and transmission bandwidth, so it shows limitations. At present, most of the researches are based on the random distribution of network nodes, only focusing on the local connection characteristics of nodes in the network, while ignoring the regularity of node distribution. In order to describe the characteristics of real networks, control networks, reduce congestion and improve network lifetime, this section proposes an evolving network model based on local-area choice (ENM-LAC).

1) RELATED DEFINITIONS

Definition 1 (Degree): The degree of a node refers to the number of edges connected to the node or the number of neighbors of that node. Generally speaking, the greater the degree of nodes is, the more important the nodes are in the network, and the greater the capacity in one aspect is. The average degree of all nodes in the network is called Average Degree, as $\langle k\rangle = (1/N)\sum_i k_i$.

Definition 2 (Degree Distribution): Refers to the distribution of node degree in the network, as $P(k)$, and indicates that the degree of random nodes in the network is k probability. $P(k) = N(k)/N$, where N is the total number of nodes in the network and $N(k)$ is the number of nodes with degree k. Usually, $P(k)\rangle 0$, and $\sum P(k) = 1$.

Definition 3: The number of edges connecting the node pairs with degrees k_i and k_j in the network is defined as $E_{k_ik_j}(k_i \neq k_j)$. The number of nodes in the network with a degree k is $N_k = NP(k)$. The joint probability distribution is defined as $P(k_i, k_j)$: It means the probability that the degrees of two nodes connected by an arbitrarily selected edge are respectively k_i and k_j.

$$P\left(k_i, k_j\right) = \frac{E_{k_ik_j}}{\langle k\rangle N} \tag{3}$$

Besides, there is

$$P(k_i) = \frac{N_{k_i}}{N} = \frac{\left(\sum_{k_j} E_{k_ik_j}/k_i\right)}{N} = \frac{\langle k\rangle}{k_i}\sum_{k_j} P\left(k_i, k_j\right) \tag{4}$$

where $\langle k\rangle = \sum_k kP(k)$.

Definition 4: For any node i to j, their node degrees are respectively k_i and k_j, then an edge is established between them, that is, the connection probability of the node is $r\left(k_i, k_j\right)$. Where $r\left(k_i, k_j\right) \geq 0$, and $r\left(k_i, k_j\right) = \left(k_j, k_i\right)$.

$$r\left(k_i, k_j\right) = \frac{E_{k_ik_j}}{N_{k_i}N_{k_j}} = \frac{\langle k\rangle}{N}\frac{P\left(k_i, k_j\right)}{P\left(k_i, k_j\right)} \tag{5}$$

We only consider the case where the degree of node is not relevant, so there is

$$P\left(k_i, k_j\right) = \frac{k_iNP(k_i)}{N\langle k\rangle}\frac{k_jNP\left(k_j\right)}{N\langle k\rangle} = \frac{k_ik_jP(k_i)P\left(k_j\right)}{\langle k\rangle^2} \tag{6}$$

It can be obtained by the formula (3) and (4)

$$r\left(k_i, k_j\right) = \frac{k_ik_j}{N\langle k\rangle} \tag{7}$$

Definition 5: The expression of the n-th moment of degree is as follows:

$$\left\langle k^2\right\rangle = \sum_k k^nP(k) \tag{8}$$

2) ESTABLISHMENT OF THE ENM-LAC MODEL

The terminals of MANET are constrained by energy, and the link distance affects the state of its wireless channel. According to the literature [33], the nodes in MANET have the choice rule of local-area preference. According to this characteristic, this section proposes a the evolving network model based on local-area choice (ENM-LAC), and analyzes and proves the scale-free property of the model based on the complex network theory. The ENM-LAC model is described as follows:

(1) Joining the new nodes: First, the network is initialized. The network initially has a small number of nodes, and the number of nodes is set to m_0, the m_0 nodes are connected to their neighboring nodes according to the distance between the nodes in its own coverage. In order to avoid the existence of isolated nodes, the network is in a connected state, which reduces the complexity of the initial network and simplifies the connection rules of the initial node.

After completing the network initialization, a new node is added to the network at a time step. The joined node chooses the location in the network based on the local-area preference, that is, the node chooses the appropriate location to join in the specific scope of the network based on the specific network property. The characteristics of network include the degree of node, the betweenness of node, node energy or other physical properties [33]. We regard the degree of node as the basis of choosing nodes to join the network. Choice probability formula for new nodes (9):

$$P_{area} = \frac{\sum\limits_{i \in local-area} k_i}{\sum\limits_{N} k_i} \tag{9}$$

where, A represents the probability of a new node joining a specific area. We call the specific area as the choice region, and the radius of this region is called the node's choice radius, which is denoted as L. The degree of node in the network is denoted as k, and $\sum\limits_{i \in local-area} k_i$ represents the degree summation of all nodes in the choice region. From formula (9), the new node chooses the location to join based on the sum of degrees of all nodes in the choice region. The sum of the degree of nodes reflects the degree of activity of the nodes in the region, and also indicates that the number of nodes in the region is large and the connections between the nodes are tight. This characteristic reflects the social attributes of MANET, and provides a basis for the detailed studying the real MANET.

(2) Preferential connection: After the new node selectively joins the network, the node will choose m nodes to connect in its coverage. The connection probability between the new node j and the existing node I in the new node's coverage area is marked as $\prod_i$, and the connection probability is constrained by the node degree and the distance between two nodes while considering the residual energy E of node i.

$$\prod_i = \frac{f\left(E_i, d_{ji}\right) k_i}{\sum\limits_{q \in local-area} f\left(E_q, d_{jq}\right) k_q} \tag{10}$$

where $f\left(E_i, d_{ji}\right) = E_i^{\alpha}\left(1 - \frac{d_{ji}}{\sum d_{ji}}\right)^{1-\alpha}$. According to formula (10), the closer the distance between the two nodes, the greater the residual energy E of node I, and the greater the probability of the connection between the new node and node i. The new node can choose the nodes that are closer to it, which can improve the quality of the channel. α is used as a tunable parameter to adjust the relationship between energy and distance according to the actual situation.

3) PROPERTY ANALYSIS OF THE MODEL

When analyzing MANET based on complex networks, the analysis of topological structure models is often carried through the degree distribution, which is an important statistical physical feature. In general, there are many methods to study the degree distribution characteristics of real complex networks, such as the mean-field method based on the continuous transformation theory [33], [34], master equation method [35], rate-equation approach [36], [37] and so on. We use the mean-field method to analyze the proposed ENM-LAC evolution model. Barabasi and Albert developed the mean-field method to describe the dynamic characteristics of scale-free networks. This method sets the network generation process to be continuous. In order to obtain the distribution of node degree, this method applies differential equations appropriately to simplify the network generation model. Based on the mean-field method, the distribution of node degree and probability density function of the topological model is obtained, and then the ENM-LAC evolution model proposed by us is analyzed.

At each time step, m new edges are created, so there is

$$\frac{\partial\left(k_i\right)}{\partial\left(k_j\right)} \approx m \prod_i = m \frac{f\left(E_i, d_{ji}\right) k_i}{\sum\limits_{q \in local-area} f\left(E_q, d_{jq}\right) k_q} \tag{11}$$

where k_i represents the degree of node i that is already in the network; at each time step, the number of edges generated by the new node j connecting to other nodes is counted as m. $\prod_i$ indicates the probability that the new node j will connect with the existing node i.

So, obtain

$$\sum_{q \in local-area} f\left(E_q, d_{qi}\right) k_q = \sum_{q \in local-area} E_q^{\alpha}\left(1 - \frac{d_{qi}}{d_{qi}}\right)^{1-\alpha} k_q \tag{12}$$

The total number N of nodes in the network is set up is large enough, and the number of nodes connected to the newly joined nodes is large, then $\frac{d_{qi}}{\sum\limits_{q=1}^{n} d_{qi}} = 0$,

And there is

$$\sum_{q \in local-area} f\left(E_q, d_{qi}\right) k_q = n \cdot E_{average}^{\alpha} \langle k \rangle \tag{13}$$

The number of nodes in the coverage area of the new node j is counted as n; the average energy of the nodes in the coverage area is counted as $E_{average}^{\alpha}$; and the average degree of nodes in the coverage area is recorded as $\langle k \rangle$.

In the large scale-free networks, the average node degree can be calculated as follows:

$$\langle k \rangle = \frac{2\left(mt + e_0\right)}{m_0 + t} \approx 2m \tag{14}$$

The e_0 and m_0 represent the number of links and the number of nodes in the initial state of the network, both of which are small.

Bring the formula (12) (13) into the formula (10) and get

$$\frac{\partial\left(k_i\right)}{\partial\left(t\right)} = \frac{f\left(E_i, d_{ji}\right) k_i}{2nE_{average}^{\alpha}} \tag{15}$$

Organize the equation (15) and get

$$\frac{\partial\left(k_i\right)}{k_i} = \frac{f\left(E_i, d_{ji}\right)}{2nE_{average}^{\alpha}} dt \tag{16}$$

Solve the differential equation and obtain

$$k_i = e^{\frac{f\left(E_i, d_{ji}\right)}{2nE_{average}^{\alpha}} t + C} \tag{17}$$

Get $C = Ink_i + \frac{f(E_i,d_{ji})}{2nE^{\alpha}_{average}} t_i$, and due to $k_i(t_i) = m$, get

$$k_i(t) = me^{\frac{f(E_i,d_{ji})}{2nE^{\alpha}_{average}}(t-t_i)} \tag{18}$$

Therefore, the probability that the degree $k_i(t)$ of node I is less than the average degree K of node is

$$P(k_i(t)\langle k) = P\left(t - \frac{f(E_i, dq_{ji})}{2nE^{\alpha}_{average}} In\left(\frac{k}{m}\right)\langle t_i\right) \tag{19}$$

The probability density function at time t_i is $P_i(t_i) = \frac{1}{m_0+t}$, so it is obtained

$$\begin{aligned} P(k_i(t)\langle k) &= 1 - P\left(t_i \le t - \frac{f(E_i, d_{ji})}{2nE^{\alpha}_{average}} In\left(\frac{k}{m}\right)\right) \\ &= 1 - \frac{1}{m_0+t}\left(\frac{f(E_i, d_{ji})}{2nE^{\alpha}_{average}} In\left(\frac{k}{m}\right)\right) \end{aligned} \tag{20}$$

The probability density function of node degree considering the residual energy of nodes and the distance relationship between two nodes is

$$P(k_{E,d}) = \frac{\partial P(k_i(t)\langle k)}{\partial k} = \frac{1}{m_0+t}\left(\frac{2nE^{\alpha}_{average}}{f(E_i, d_{ji})}\frac{m}{k}\right) \tag{21}$$

The continuous random variable of node degree is marked as k. Through the weighted average of the function, the probability density function of the network is obtained as

$$P(k) \propto \theta k^{-1} \tag{22}$$

$\theta = \int_E \int_d \mu\sigma p(k_{E,d}) dddE$ is the distribution E and d respectively.

Equations (21) and (22) show that the power law form of the distribution function of the proposed model includes exponential $\lambda = -1$. It is shown that the proposed ENM-LAC model can evolve to generate scale-free networks. Due to the constraints of the generating model, the scale-free property of the generated MANET is lower than that of the BA model.

The above analysis shows that under the premise of energy and link distance of the network node, the ENM-LAC model, which takes into account the location characteristics of new nodes when they join the network, can generate a scale-free MANET that obeys the characteristics of the scale-free network.

B. ANALYSIS AND CALCULATION OF ASPL OF NETWORK BASED ON ENM-LAC

In the above, we describe the evolving network model based on local-area choice in detail, and how to compute degree distribution and edge connection probability function according to the evolution model. Next we describe how to calculate topology properties statistics according to the evolving network model based on local-area choice, that is, to compute ASPL.

Lemma 1 [40]: Suppose $A_1, \ldots, A_w$ are independent events and the probability of occurrence is $\forall_h P(A_h) \le \varepsilon$.

$$P\left(\bigcup_{h=1}^{w} A_h\right) = 1 - \exp\left(-\sum_{h=1}^{w} P(A_h)\right) - Q \tag{23}$$

Where $0 \le Q\langle \sum_{v=0}^{h+1}(n\varepsilon)^v/v! - (1+\varepsilon)^h$.

Proof: According to the inclusion and exclusion principle [38] in combinatorial mathematics and probability theory, there is

$$P\left(\bigcup_{h=1}^{w} A_h\right) = \sum_{g=1}^{w}(-1)^{g+1} S(g) \tag{24}$$

$$\begin{aligned} S(g) &= \sum_{1\le h_1\langle h_2\langle\ldots\langle h_g\le w}^{w} P(A_{h_1}) P(A_{h_2})\ldots P(A_{h_g}) \\ &= \frac{1}{g!}\left(\sum_{g=1}^{w} P(A_h)\right)^g - Q_g \end{aligned} \tag{25}$$

where, $0 \le Q_g \le \left(w^g/g! - \binom{w}{g}\right)\varepsilon^g$, and item Q_g is ignored, then the first $n+1$ terms of McLaughlin expansion $\exp\left(-\sum P(A_h)\right)$ equal $1 - P\left(\bigcup A_h\right)$. The higher-order term of Maclaurin expansion is considered as an error and less than $R\langle (n\varepsilon)^{w+1}/(n+1)!$. And there is an error $Q\langle \sum_{g=1}^{w} Q_{Gg} + R$ of the formula (23), so as to complete the proof of the formula (23). When $\varepsilon = A/n\langle\langle 1$, the total error is less than $A^2 \exp(A)/n$, and tends to 0 with $n \to \infty$.

We analyze the ASPL problem of MANET through complex network theory. Set a walk, the length is labeled x, and the sequence of nodes contained in the walk is $\{i, v_1, v_2 \ldots v_{(x-1)}, j\}$. According to the above, combined with the definition 4, the edge is established between two nodes and the connection probability is recorded as $\tilde{p}_{ij} = r(k_i, k_j)$. The probability of the existence of this walk can be recorded as $\tilde{p}_{iy_1}\tilde{p}_{y_1y_2}\tilde{p}_{y_2y_3}\ldots\tilde{p}_{y_{(x-1)}j}$. When the nodes that make up a wall are not the same, the walk is called the path, and we focus on the shortest path. If there is a path between nodes I and j, the length is recorded as x, which is the x edges that make up the path. Assuming that this path is the shortest path we want to study, nodes i and j are the x-th order neighbors; otherwise, they are neighbors closer to each other. The probability that there is at least one path between nodes I and j, the length of which is x, is set to $\tilde{p}_{ij}(x)$, or the probability that the neighbor order between two nodes is not greater than x. The probability expressions that the nodes i and j are exactly each other's x order neighbors is as follows:

$$p^*_{ij}(x) = \tilde{p}_{ij}(x) - \tilde{p}_{ij}(x-1) \tag{26}$$

Now consider the existence of a path as a random event, using lemma 1, there is

$$\tilde{p}_{ij}(x) = 1 - \exp\left[-\sum_{y_1=1}^{N}\ldots\sum_{y_{x-1}=1}^{N}\tilde{p}_{iy_1}\ldots\tilde{p}_{y_{(x-1)}j}\right] \tag{27}$$

where N denotes the number of nodes in the network, and the path $\{i, y_1, \ldots, y_{(x-1)}, j\}$ constructed by $(x+1)$ nodes corresponds to a random event recorded as A_i. There are a total of $n = N^{x-1}$ such random events. According to the above equations (7) and (27), it can be calculated:

$$\begin{aligned}\tilde{p}_{ij}(x) &= 1-\exp\left[-\sum_{y_1=1}^{N}\cdots\sum_{y_{x-1}=1}^{N}\frac{k_i k_{y_1}}{N\langle k\rangle}\cdots\frac{k_{y_{(x-1)}}k_j}{N\langle k\rangle}\right]\\ &= 1-\exp\left[-\frac{k_i k_{y_1}N^{(x-1)}}{(N\langle k\rangle)^x}\left(\sum_{y_1=1}^{N}\frac{k_{y_1}^2}{N\langle k\rangle}\cdots\right.\right.\\ &\qquad\left.\left.\times\left(\sum_{y_{x-1}=1}^{N}\frac{k_{y_{(x-1)}}^2}{N}\right)\right)\right]\\ &= 1-\exp\left[-\frac{k_i k_j}{\langle k^2\rangle N}\left(\frac{\langle k^2\rangle N}{\langle k\rangle N}\right)^x\right] \end{aligned} \tag{28}$$

The probability formula (26) that the two node are x order neighbors is recorded as:

$$p_{ij}^{*}(x) = F(x-1) - F(x) \tag{29}$$

where,

$$F(x) = \exp\left[-\frac{k_i k_j}{\langle k^2\rangle N}\left(\frac{\langle k^2\rangle N}{\langle k\rangle N}\right)^x\right] \tag{30}$$

The formula (23) of Lemma 1 is established when each event A_h is independent of each other. But there are multiple paths sharing a node in the network, resulting in non-independence in the real network. Because of the small-world nature of MANET [39], the distances between nodes in real networks are often very short, so we can ignore the network correlation when the path length is much smaller than the size of the network.

Theorem 1: In MANET, the probability that there is at least one path of length x between nodes I and j is set to $\tilde{p}_{ij}(x)$, that is, the probability that the neighbor order between two nodes is not greater than x. Then the expected value of the shortest path length between nodes I and j is:

$$l_{ij}(k_i, k_j) = \frac{-Ink_ik_j + InN + In\langle k^2\rangle - \gamma}{InN + In\langle k^2\rangle - In\langle k\rangle N} + \frac{1}{2} \tag{31}$$

Where $\gamma \cong 0.5772$ is Euler's constant.

Proof: According to equation (29), the expected value of the shortest path length between nodes i and j in the MANET is calculated:

$$\begin{aligned} &l_{ij}(k_i, k_j)\\ &= \sum_{x=1}^{\infty} xp_{ij}^{*}(x) = \sum_{x=1}^{\infty} F(x)\\ &= \frac{1}{2}F(0) + \int_0^{\infty} F(x)dx + 2\sum_{n=1}^{\infty}\left(\int_0^{\infty} F(x)cos(2n\pi x)dx\right)\\ &= \frac{1}{2} + \left[-Ei\left(-\frac{k_ik_j}{\langle k^2\rangle N}\right)\Big/In\left(\frac{\langle k^2\rangle N}{\langle k\rangle N}\right)\right] + 0\\ &= \frac{-Ink_ik_j + InN + In\langle k^2\rangle - \gamma}{InN + In\langle k^2\rangle - In\langle k\rangle N} + \frac{1}{2} \end{aligned}$$

The second to third lines of the above formula are derived from the Poisson summation formula. Where $(k_ik_j)/(\langle k^2\rangle N) \approx 0$, so $F(0) = 1$. In addition, the second term of the third line derived from the second term of the second line is the exponential integral function, which satisfies $Ei(-y) = \gamma + Iny$, and $\gamma \cong 0.5772$ is Euler constant. Finally, the first term of the fourth line is obtained. Theorem 1 is proved.

The average length of all the shortest paths in the whole network is:

$$l = \frac{-2\langle Ink\rangle + InN + InN\langle k^2\rangle - \gamma}{InN + In\langle k^2\rangle - In\langle k\rangle N} + \frac{1}{2} \tag{32}$$

The analysis and calculation for ASPL of network based on ENM-LAC are as follows.

Because $r(k_i, k_j) = \frac{\partial(k_i)}{\partial(t)}$, according to formula (13) (16) it can be derived:

$$r(k_i, k_j) = \frac{m}{2nE_{average}^{\alpha}}e^{\frac{f(E_i, d_{ji})}{2nE_{average}^{\alpha}}(t-t_i)} \tag{33}$$

Combined the equation (5) (33), it can be obtained:

$$k_ik_j = \frac{m^2}{E_{average}^{\alpha}}e^{\frac{f(E_i, d_{ji})}{2nE_{average}^{\alpha}}(t_j-t_i)} \tag{34}$$

In the ENM-LAC model, node degree is considered as the basis for nodes to join the network.

According to theorem 1, the node degree distribution (22) and formula (34) are substituted into equation (31).

$$l_{ij}(k_ik_j) = e^{\frac{1}{In\theta}}\frac{Ink_ik_j - In(m/2) - \gamma}{InInN + In(m/2)} + \frac{3}{2} \tag{35}$$

According to equation (35), average all nodes, and the ASPL formula based on the model network can be calculated:

$$l = e^{\frac{1}{In\theta}}\frac{InN - In(m/2) - 1 - \gamma}{InInN + In(m/2)} + \frac{3}{2} \tag{36}$$

The number of nodes in the coverage of the new node j is denoted as n, which is related to the coverage radius R of node j.

C. THE IMPACT OF RANDOM EDGE FAILURE ON ASPL OF THE NETWORK BASED ENM-LAC

In order to study the change of ASPL in MANET after random edge failure, we propose a theoretical formula based on ENM-LAC.

Theorem 2: In a random scenario, if f probability of edge in the topology of MANET is randomly deleted (the probability of any edge being deleted is f), the degree distribution in the network becomes

$$P_f(k) = \sum_{k_0=k}^{\infty} P(k_0)\binom{k_0}{k}(1-f)^k f^{k_0-k} \tag{37}$$

Correspondingly, the first and second order central moments of the new degree distribution can be obtained respectively as:

$$\langle k\rangle_f = (1-f)\langle k\rangle \tag{38}$$

$$\left\langle k^2\right\rangle_f = \left\langle k_0^2\right\rangle (1-f)^2 + \langle k_0\rangle f(1-f) \tag{39}$$

Proof:

$$\begin{aligned}\langle k\rangle_f &= \sum_{k=0}^{\infty} kP_f(k) = \sum_{k=0}^{\infty} k \sum_{k_0=k}^{\infty} P(k_0)\binom{k_0}{k}(1-f)^k f^{k_0-k}\\ &= \sum_{k_0=0}^{\infty} P(k_0)\sum_{k=0}^{\infty} k\binom{k_0}{k}(1-f)^k f^{k_0-k}\\ &= \sum_{k_0=0}^{\infty} P(k_0)\left(k_0(1-f)\sum_{k=1}^{k_0}\binom{k_0-1}{k-1}(1-f)^{k-1}f^{k_0-k}\right)\\ &= \sum_{k_0=0}^{\infty} P(k_0)\,k_0(1-f)\left((1-f)+f\right)^{k_0}\\ &= (1-f)\langle k_0\rangle\end{aligned}$$

Equation (38) is proved.

Proof:

$$\begin{aligned}\left\langle k^2\right\rangle_f &= \sum_{k=0}^{\infty} k^2 P_f(k) = \sum_{k=0}^{\infty} k^2 \sum_{k_0=k}^{\infty} P(k_0)\binom{k_0}{k}(1-f)^k f^{k_0-k}\\ &= \sum_{k_0=0}^{\infty} P(k_0)\sum_{k=0}^{\infty} k^2\binom{k_0}{k}(1-f)^k f^{k_0-k}\\ &= \sum_{k_0=0}^{\infty} P(k_0)\,k_0(1-f)\left(\sum_{k=1}^{k_0}(k-1)\binom{k_0-1}{k-1}\right.\\ &\qquad \left.\times(1-f)^{k-1}f^{k_0-k} + \sum_{k=1}^{k_0}\binom{k_0-1}{k-1}(1-f)^{k-1}f^{k_0-k}\right)\\ &= \sum_{k_0=0}^{\infty} P(k_0)\,k_0(1-f)\left((k_0-1)(1-f)+1\right)^{k_0}\\ &= \left\langle k_0^2\right\rangle(1-f)^2 + \langle k_0\rangle f(1-f)\end{aligned}$$

Equation (39) is proved.

For the generated MANET topology based on ENM-LAC, edges are randomly deleted in proportion f. According to theorems 1 and 2, node degree distribution (22) and formula (34) are substituted into equation (31) to obtain:

$$l_{ij}\left(k_ik_j\right) = e^{\frac{1}{In\theta}}\frac{Ink_ik_j - In(m/2) - \gamma}{InInN + In(m/2) + In(1-f)} + \frac{3}{2} \tag{40}$$

By calculating the average value of all nodes by equation (40), we calculate the ASPL formula of MANET at this time.

$$l = e^{\frac{1}{In\theta}}\frac{InN + InInN - \gamma - 1}{InInN + In(m/2) + In(1-f)} + \frac{1}{2} \tag{41}$$

D. THE ANALYSIS FOR COMPUTATIONAL COMPLEXITY OF ENM-LAC

For constructed MANET based on ENM-LAC, we theoretically calculate time and space (complexity). Time resources are the time needed to solve problems, which are usually measured by calculating deployment. Space resources are the space needed to solve problems, usually measured by the size of storage space. The basis for measuring computational complexity is the amount of resources needed. The efficiency or complexity of an algorithm is expressed as a function whose domain is the size of the input data (length, most algorithms are designed to allow any length to the input), and the range of values is usually the number of steps to be performed (time complexity) or the amount of storage space required (space complexity).

Inferences 1: The space complexity of the ENM-LAC algorithm is $O(n^2)$.

Proof: In the process of constructing MANET based on ENM-LAC algorithm, new nodes are added constantly. Therefore, it is more suitable to use the adjacency matrix of graph to represent the network construction. In this algorithm, each new node needs to store the location preference information and the preferred choice situation when it joins the network, so the space complexity is $O(n^2)$.

Inferences 2: The time complexity of the ENM-LAC algorithm is $O(n)$.

Proof: The time complexity of ENM-LAC algorithm is determined by network growth and node preference link. Every node that is newly added has to go through these two processes. In the algorithm, only two initial nodes are connected to each other in the initial state $m_0 \geq 2$ of the network. On the process of network construction, new nodes are added based on location preference, and the worst time complexity of this process is $O(n_1)$; new nodes connect to the existing nodes within the coverage of the new nodes, and the worst time complexity of this process is $O(n_2)$. We make the $n = n_1 + n_2$, the time complexity of the ENM-LAC algorithm is $O(n)$.

IV. THE ALGORITHM DESIGN OF DYNAMIC ANALYSIS FOR THE MANET TOPOLOGY

According to the ENM-LAC, we first generate a large number of MANET networks satisfying the specified local choice preference, then select one of the networks and delete the edges randomly at the ratio of f, that is, pick out the edges with the f ratio from the edge set randomly and delete them. Finally calculate the average of the shortest path between any pair of nodes in the network after deleting the edges randomly, that is, the ASPL of the network. Each time the network is generated, the above process is executed. Finally, the average value of the all computed ASPL of the generated networks is calculated again.

(1) Establish the MANET based on ENM-LAC.

① Network initialization: At the beginning of the network, set the number of nodes as m_0, the m_0 nodes are connected to their neighbor nodes according to the distance between the nodes in its own coverage.

② Network growth: Set the radius of the choice region as L. First calculate the sum of the degree of nodes in the choice region, and then calculate the choice probability according to Eq. (9). The area with the maximum choice probability is chosen as the location choice area added by the new node. Pseudo code is part A. If the coverage of the new node is larger than that of the choice region, the center of the choice region is determined as the coordinate of the new node. Otherwise, in the choice region, the position where the maximum degree of nodes within the coverage of the new node is determined as the position of the new node adding to the region. Pseudo code is part B.

Algorithm 1 (Network Growth:) The pseudo code of the algorithm for node joining the network based on location preference.

```
A: {
    $Parea = (deg\ ree2)/sum(deg\ ree1);$
    $//The\ probability\ \exp\ ression\ followed$
    $//when\ new\ nodes\ join\ the\ network$
        $[V, I] = max(Parea);$
    $//Finding\ max\ imum\ probability\ of\ choice$
    $indx\ 2 = find(Parea >= 0.5^{*} V);$
    $\%Nr = randperm(length(indx2));$
        $Nr = floor(length(indx2)^{*} rand) + 1;$
        $if\ rand > \max([0.5, sum(Parea(1:m))])$
    $//Sum\ of\ node\ deg\ ree\ within\ node\ coverage$
}
B: {
    $if\ rand > Vp(end - m + 1)$
            $Xnew = X2(indx2(Nr)) + L^{*} \cos(2^{*} pi^{*} rand);$
    $//Calculating\ the\ X\ coordinate\ of\ new\ node$
            $Ynew = Y2(indx2(Nr)) + L^{*} \sin(2^{*} pi^{*} rand);$
    $//Calculating\ the\ Y\ coordinate\ of\ new\ node$
        $else$
            $Xnew = rand(1, 1)^{*} SCALE;$
    $///Calculating\ the\ X\ coordinate\ of\ new\ node$
            $Ynew = rand(1, 1)^{*} SCALE;$
    $///Calculating\ the\ Y\ coordinate\ of\ new\ node$
        $end$
}
```

③ Preferential connection: When a new node selectively enters the network, it first determines whether the existing node is in the choice area and is covered by the new node, and then calculates the remaining energy of the existing node i in the coverage area of the new node j, the connection distance between the new node j and the existing node i and the node degree of the existing node i in the choice area. According to the connection probability formula (10), the connection probability of the new node j is calculated, and m nodes within its coverage are selected to connect. The algorithm is shown below. Considering the mobility and location preference, the MANET network is built.

Algorithm 2 (Preferential Choice): Pseudo-code for calculating the node degree of existing node i and the connection distance between two nodes in the choice area of a new node

```
$indx = indx + 1; rng(indx);$
$//Calculating\ the\ node\ degree$
$if\ indx == 1 X2 = X; Y2 = Y; end$
  $degree1 = []; fori = 1 : length(X2)\ xx = 0;$
$for\ j = 1 : length(Y2)$
   $dist = sqrt((X2(i) - X2(j))^{\wedge}2 + (Y2(i) - Y2(j))^{\wedge}2);$
$//The\ distance\ between\ two\ nodes$
$if\ dist <= Radius\ \&\ dist > 0$
$//The\ node\ i\ within\ the\ new\ node\ coverage\ is\ not$
$//\quad in\ the\ choice\ region.$
 $xx = xx + 1; end\ end\ degree1(i) = xx;$
  $end$
   $degree2 = []; di = []; for\ i = 1 : length(X2)xx = 0;$
$for\ j = 1 : length(Y2)$
   $dist = sqrt((X2(i) - X2(j))^{\wedge}2 + (Y2(i) - Y2(j))^{\wedge}2);$
$//Spatial\ distance\ between\ nodes$
    $if\ dist <= Radius\&dist > 0\&dist <= L$
$//The\ node\ i\ within\ the\ new\ node\ coverage\ is$
           $//\ in\ the\ choice\ region$
            $xx = xx + 1; end$
         $di(i, j) = dist;$
$//The\ distance\ between\ two\ nodes$
          $end$
          $degree2(i) = xx;$
$//The\ degree\ of\ node\ i\ in\ the\ choice\ region$
         $end$
```

Algorithm 3 (Preferred Connection): Pseudo-code for calculating the preferred connection probability

```
$if\ indx == 1$
   $E(1 : m0) = E0 - Ec; tmps = E; else$
  $E = tmps - Ec; E = [E, E0 - Ec]; tmps = E;$
   $end$
    $for\ i = 1 : length(X2)\quad d = di(i, :);$
$fed(i) = E(i)^{\wedge}alpha^{*}(1 - d(i)/sum(d))^{\wedge}(1 - alpha);$
$//The\ constraint\ of\ residual\ energy\ of$
  $//\ node\ i\ and\ distance\ between\ nodes$
    $end$
    $for\ i = 1 : length(X2)$
$Para2(i) = fed(i)^{*}\ degree2(i)/(sum(fed.^{*}\ degree1));$
$//The\ constraint\ of\ residual\ energy$
   $//\ node\ degreeand\ distance\ between\ nodes$
    $end$
    $[Vp, Ip] = sort(Para2);$
$//Selecting\ the\ m\ nodes\ with\ the\ highest$
   $//\ probability\ to\ connect$
   $Mindx = Ip(end - m + 1 : end);$
```

(2) ASPL algorithm for MANET with local choice preference (i.e. MANET based on ENM-LAC model): Equation (33) (34) is first computed. According to lemma 1 and theorem 1, the expected value of the shortest path length

between node i and node j in MANET based on ENM-LAC model is calculated, that is, equation (35). Then we average all the nodes to get the theoretical calculation equation (36) of ASPL of the MANET based on model.

Algorithm 4 (ASPL Algorithm): Pseudo code of ASPL algorithm for MANET with local choice preference is shown below.

```
Eavg = mean(E);
    n = xx; ms = m; t = 0.005 * indx; k = mean(degree1);
    Pked = 1/(m0 + t) * (2 * n * Eavg./fed * ms/k);
//Connectionprobabilitybetweentwonodes, formula(33)
    dt = 0.1; theta = sum(Pked);
      kikj = ms^2/Eavg * exp(fed/(2 * n * Eavg) * dt);
// formula(34)
    gamma = 0.5772;
LLs = exp(1/log(theta)) * ( − 1 * log(kikj) − log(ms/2)
        − gamma)/(log(log(N)) + log(ms/2))) + 3/2;
//The expectedaverage of the shortest path lenth between
    //teo nodes in the MANET with local-area
// perference, formula(35)
    Lens(indx) = mean(LLs);
Ls = exp(1/log(theta)) * ((log(log(N))−
        gamma − 1)/(log(log(N)) + log(ms/2))) + 1/2;
```

(3) ASPL changes after random edge deletion: Assume that the probability of any edge being deleted is f. And the network is still connected, so we only test the small deletion of edges, $0 \leq f \leq 1$. According to theorem 2, the expected value of the shortest path length between node i and node j after the random edge deletion occurring in the network with location choice preference is calculated, that is, the equation (40). Then we average all the nodes to get the ASPL formula (41) after the random edge deleted from the network.

Algorithm 5 (ASPL Algorithm After The Random Edge Failure): Set deleted probability is f, and the pseudo-code of ASPL algorithm of network with location preference in random failure scenario is shown below.

```
Eavg = mean(E);
     n = xx; ms = m; t = 0.005 * indx; k = mean(degree1);
     Pked = 1/(m0 + t) * (2 * n * Eavg./fed * ms/k);
//connection probability between two nodes
     dt = 0.1; theta = sum(Pked);
     kikj = ms^2/Eavg * exp(fed/(2 * n * Eavg) * dt);
//formula (34)
     gamma = 0.5772;
LLsf = exp(1/log(theta)) * (log(kikj)−log(ms/2)−gamma)/
         (log(log(N)) + log(ms/2) + log(1 − f))) + 3/2;
//Setting deleting probability is f, the expectedaverage
//of the shortest path lenth between teo nodes
//in the MANET with local-area perference, formula(40)
    Lens(indx) = mean(LLs);
Lsf = exp(1/log(theta)) * ((log(log(N)) − gamma−
        1)/(log(log(N)) + log(ms/2) + log(1 − f))) + 1/2;
        //formula(41)
```

Through experimental simulation and actual scene test, it is proved that the proposed theoretical formula is strictly consistent with the experimental results. Many dynamic processes in MANET are related to the shortest path, such as routing technology, one of the most critical technologies in MANET. In real networks, random failures occur frequently, so our research has a guiding practical significance for the in-depth study of MANET structure and the construction of the network. It also has theoretical guiding significance for the research on the invulnerability of networks.

V. SIMULATIONS AND TEST IN REAL SCENARIOS

The above theoretical analysis is verified by numerical simulation using MATLAB software. Firstly, the node degree distribution of ENM-LAC model and the change of ASPL of network are simulated under different conditions. The changes of ASPL of network are analyzed when random failures occur. The theoretical results and real results are tested in real scenarios. The comparison test results show that under different conditions, the theoretical calculation formula of ASPL is consistent with the actual results. It proves the practical significance of our research.

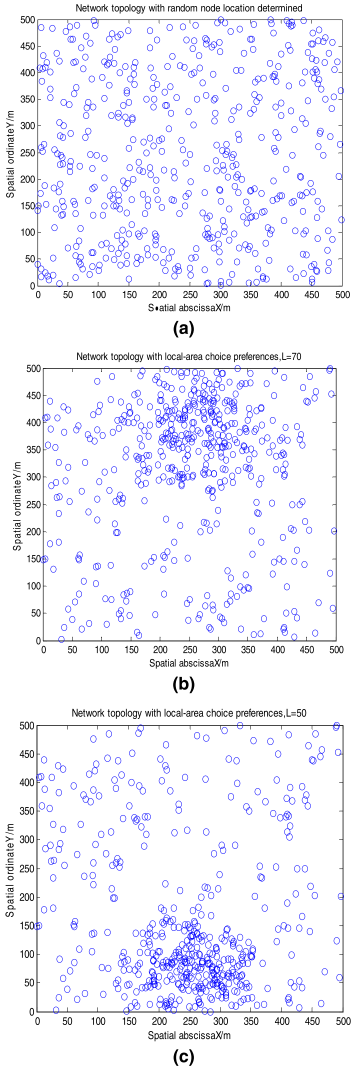
A. SIMULATIONS AND ANALYSIS

In the simulation, it is assumed that the network does not perform the data transmission process. Firstly, the node degree distribution of the proposed ENM-LAC model is simulated under different radius of choice region, different coverage of nodes and different energy consumption of nodes. Then, under different simulated conditions, the changes of ASPL of the network are simulated, and the changes of ASPL of the network are simulated when random failures occur. The simulation parameters are shown in table 1.

TABLE 1. **Simulation parameters.**

Node distribution range	500(m)×500(m)
Total number of nodes	500
Initial energy of node E_0	1J
Energy consumption at one time step E_c	1/1000
Initial number of nodes m_0	9
Number of each node connected to the local area	8

Figure 3 depicts the influence of node choosing a different location in the generated topology of the MANET. The figure (a) represents the MANET topology in which nodes randomly choose the location in the network, that is, new nodes can randomly choose the location to join in the whole scene. In the whole scenario, the nodes are all uniformly distributed, and the formed network topology is random and unfixed. The figure (b) describes the MANET topology graph that the nodes choose the location to join in network according to the local-area choice preference, and the choice radius is set to $L = 70$; and figure(c) represents the choice radius is set to $L = 50$. According to the results of figure (b)(c), with the decrease of node choice radius, the



(a)

(b)

(c)

FIGURE 3. **The network topology form with different location distribution of nodes. (a) The network topology with randomly choosing the location of nodes. (b) Network topology with local-area choice preferences (L = 70). (c) Network topology with local-area choice preferences (L = 50).**

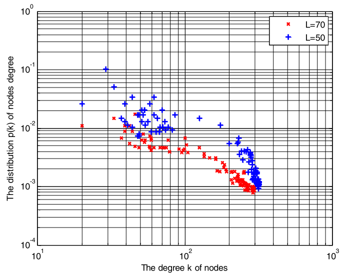


FIGURE 4. **Node degree distribution of network with different choice radius L, (R = 50, E_c = 1/2000).**

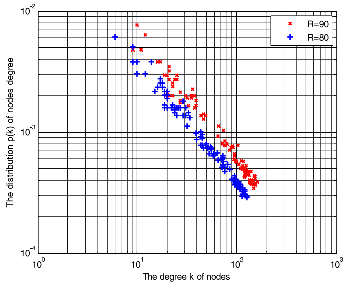


FIGURE 5. **Node degree distribution of network with different node coverage R (L = 35, E_c = 1/2000).**

distribution of nodes becomes more centralized and the degree of aggregation in the whole scene is gradually increased. It objectively reflects the evolution characteristics of the real network, but the aggregation characteristics of the network topology will reduce the connectivity of the whole network. Therefore, it should be avoided that the choice radius is too small; resulting in the phenomenon of network islands, and the generated network topology is not fully connected graph.

Figure 4 shows the effect of the choice radius L on node degree distribution of MANET generated with local-area choice preference. It can be seen from the figure that when the energy consumption E_c and coverage R of nodes are fixed, the possibility of new nodes joining the high-density area becomes smaller with the increase of the choice radius L. The characteristics of local-area choice preference are not obvious. On the contrary, as the L becomes smaller, the new node tends to choose the region with high density, and the characteristics of local-area choice preference are more obvious. In the actual MANET, the coverage of nodes is basically determined, so when the choice radius L is increased, the distribution of nodes tends to be decentralized, resulting in a larger number of nodes less than the network with a smaller choice radius.

Figure 5 depicts the effect of the different node coverage R on node degree distribution of MANET generated with local-area choice preference. We assume that all nodes in the same scene have the same coverage radius. It can be seen from the figure that when the coverage R = 90, the ratio of distribution with larger node degree is relatively increased compared with the case of R = 80. In the MANET, each node can only select the existing nodes in its own coverage R to connect. It is the existence of connection conditions that makes the degree distribution of the whole network less different than that of the network without connection conditions. As the coverage of nodes increases gradually, the possibility of new nodes connecting existing nodes with large node degree also increases, thereby increasing the difference of node degree of the whole network. When the coverage of nodes itself increases to the whole area, a MANET belonging to BA network is generated.

Figure 6 shows the node degree distribution of the network under the different node energy consumption (E_c = 1/400 and E_c = 1/4000). If the remaining energy of node in the network is larger, the node will be more easily connected by new nodes. Therefore, when the node consumes more energy in the unit time, the node latter joined the network has the greater energy difference compared with the node

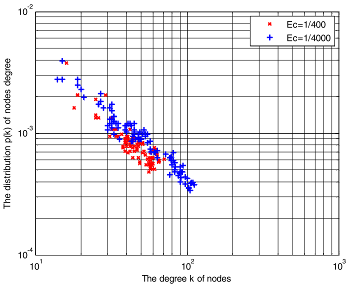


FIGURE 6. **Node degree distribution of network with different node energy consumption (R = 50, L = 35).**

former joined the network, and has the greater probability of being connected. As shown in Figure 6, when energy consumption $E_c = 1/400$ is compared with energy consumption $E_c = 1/4000$, the node with low node degree has a relatively large distribution, while the node with high node degree has a relatively low distribution. Therefore, if the energy consumption of nodes is increased, the node degree will gradually approach the average node degree of the network.

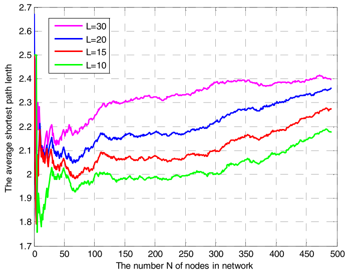


FIGURE 7. **The change of ASPL under different choice radius L (R = 50 (E_c = 1/2000).**

Figure 7 describes the influence of different choice area radius L on the ASPL of the network. When the node coverage R and energy consumption remain unchanged, the ASPL of the network increases with the increase of the choice radius L. According to the analysis of the properties of the network obtained from Figure 4, under the same conditions, the characteristics of local-area choice preference of node distribution are not obvious, and the possibility of new nodes joining high-density areas becomes smaller, which makes the shortest path become longer. On the contrary, as L becomes smaller, the characteristics of the local-area choice preference of node become more obvious. The new node tends to choose the area with high node density, and the shortest path length becomes smaller. The coverage of nodes is basically determined in MANET, so the choice radius L is increased, the distribution of nodes tends to be dispersed, and the ASPL of the network increases.

Figure 8 shows the change of ASPL in different node coverage. It can be known from Figure 5, with the increase of R, the ratio of distribution with higher node degree is relatively reduced, and the characteristics of local-area choice preference of node are not obvious. When the coverage of nodes increases to the whole area, the nodes are randomly distributed in the whole scene, and the generated network is the BA network, and the length of the shortest path increases.

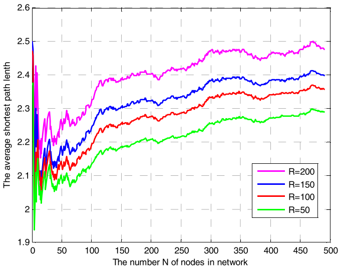


FIGURE 8. **The change of ASPL in different node coverage R (L = 35, E_c = 1/2000).**

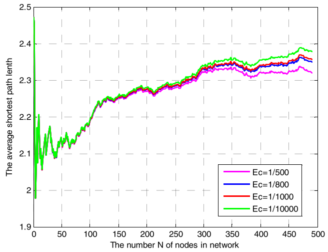


FIGURE 9. **The change of ASPL under different energy consumption of node (R = 50,L = 35).**

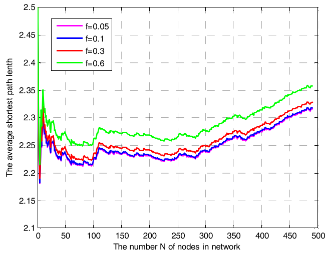
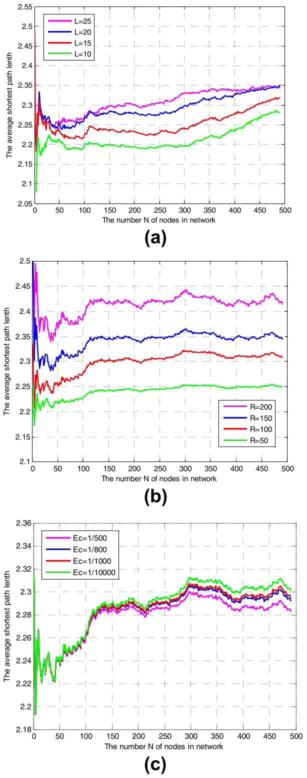


FIGURE 10. **The change of ASPL under different deletion probability (L = 35, R = 50, E_c = 1/2000).**

Figure 9 shows the change of ASPL when the energy consumption of node is different. It can be known from the simulation results in figure 6 that the node degree will gradually approach the average node degree of the network with the increase of energy consumption, and the characteristics of the local-area choice preference of the node will gradually be obvious, and the shortest path length will decrease.

Figure 10 shows that the shortest path length varies with different deletion probability, when the choice radius of node is L = 35, the coverage range is R = 50 and the unit energy consumption of node is $E_c = 1/2000$. It is shown from the figure that the ASPL of MANET increases with the increase of deletion probability. The probability of deletion is large, and the connection probability of node decreases, which leads to the increase of the average shortest path of the network.

Figure 11 respectively shows the change of ASPL with different choice radius L, different node coverage R and different energy consumption when deletion probability is f = 0.1. Compared with Figures 7, 8, 9 above, the ASPL of the network is relatively larger due to the occurrence of

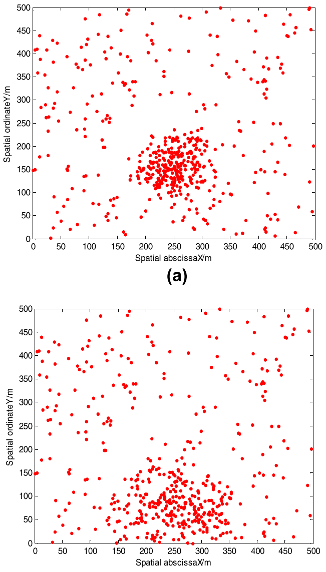


(a)

(b)

(c)

FIGURE 11. The change of ASPL under different conditions, when deletion probability is f = 0. (a) The change of ASPL under different choice radius L (R = 50, $E_c = 1/2000$). (b) The change of ASPL under different node coverage R (L = 35, $E_c = 1/2000$). (c) The change of ASPL under different energy consumption of node (R = 50, L = 35).



(a)

(b)

FIGURE 12. The network topology with local-area choice preferences under different choice radius in the real scenarios. (a) The network topology with local-area choice preferences in the real scenarios (L = 35). (b) The network topology with local-area choice preferences in the real scenarios (L = 50).

random edge failures and the loss of edges between the nodes. Figure 11 shows the trend of ASPL in the occurrence of edge failures.

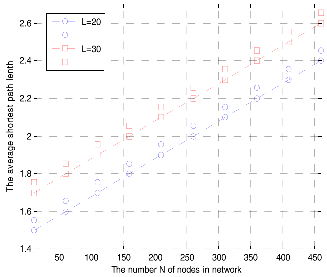


FIGURE 13. The change of ASPL with different choice radius L, (R = 50 ($E_c = 1/2000$).

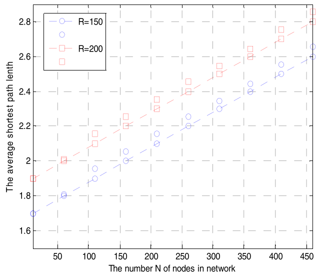


FIGURE 14. The change of ASPL in different node coverage R (L = 35, $E_c = 1/2000$).

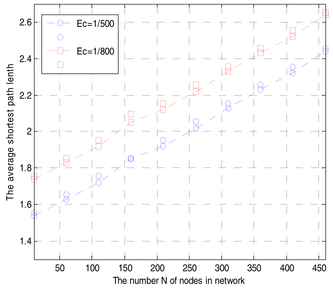


FIGURE 15. The change of ASPL with different energy consumption of node (R = 50, L = 35).

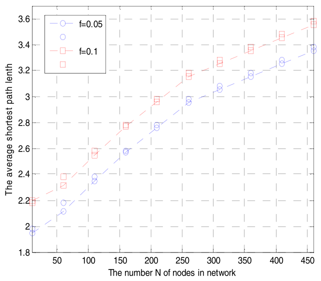


FIGURE 16. The change of ASPL with different deletion probability (L = 35, R = 50, $E_c = 1/2000$). The discrete data points represent the experimental results of the real scenarios, and the solid lines of the hollow drawings represent the theoretical formula.

B. TEST AND ANALYSIS OF REAL SCENARIOS

In recent years, frequent geological disasters in China have seriously threatened the lives and property of the Chinese people. The public security fire forces rely on the rescue of the Wenchuan earthquake in Sichuan, the Yushu earthquake

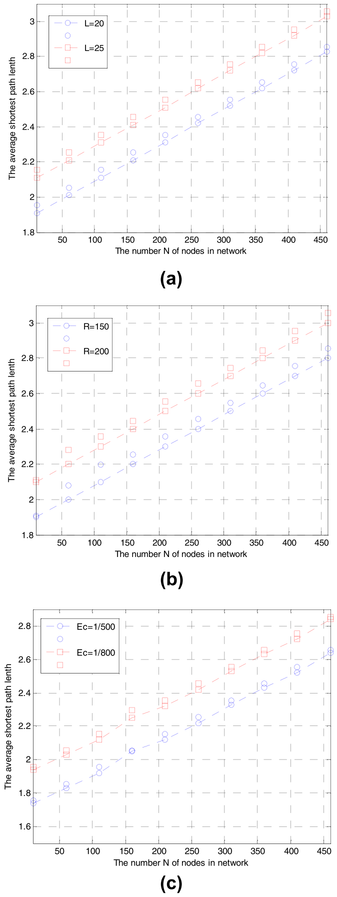


FIGURE 17. **The comparison of ASPL under different conditions, when deletion probability is $f = 0.1$. The discrete data points represent the experimental results of the real scenarios, and the solid lines of the hollow drawings represent the theoretical formula. (a) The change of ASPL under different choice radius L ($R = 50$, $E_c = 1/2000$). (b) The change of ASPL under different node coverage R ($L = 35$, $E_c = 1/2000$). (c) The change of ASPL under different energy consumption of node ($R = 50$, $L = 35$).**

in Qinghai, the debris flow in Zhouqu, and other forest disasters, which have gradually become the backbone of China's rescue. As the modern world enters the information age, real-time communication in wartime plays an increasingly important role in dispatch of firefighting and rescue of public security departments. Smooth and stable communication system has become the decisive factor of rapid mobilization of rescue forces, correct and effective ordering, and timely and comprehensive feedback.

However, due to the limitation of natural conditions, sudden communication path breaking could easily arises. Based on the random failure scenario, we test the algorithm of ASPL of MANET generated by ENM-LAC model when the random edge failures occur. The results show that the proposed theoretical algorithm is in strict agreement with the actual results of MANET, and the proposed theoretical formula provides a theoretical basis for the study of the properties of MANET.

In areas where natural disasters occur frequently, a range of 500 (m) × 500 (m) is randomly selected. Based on the ENM-LAC, the MANET in the rescue process is constructed, as shown in Figure 12. The test parameters are shown in table 2.

TABLE 2. **Test parameters.**

Node distribution range	500(m)×500(m)
Total number of nodes	500
Initial energy of node E_0	1J
Energy consumption at one time step E_c	1/1000
Initial number of nodes m_0	9
Number of each node connected to the local area	8

The discrete data points represent the experimental results of the real scenarios, and the solid lines of the hollow drawings represent the theoretical formula.

We propose a formula for calculating the ASPL of MANET after random edge failures. By applying our conclusions to the simulation and actual scenarios of MANET, the accuracy of the proposed estimation formula is verified. The proposed formula provides a general framework for studying the topology of MANET (ASPL).

VI. CONCLUSIONS AND FUTURE WORKS

Research on MANET topology is mostly based on the random distribution of nodes, but the real nodes are regularly distributed in the network. Therefore, according to the mobility and local-area choice preference of real MANET, an evolving network model based on local-area choice of MANET is proposed with the constraints of node energy consumption and link distance. The MANET based on this model is more suitable for the real network. By the mean-field method, it is proved that the ENM-LAC can generate scale-free MANET. Then, the formula for calculating the ASPL of the MANET generated by ENM-LAC and the ASPL of the network after the random edge failures (that is, the ASPL of the network after the random edge is deleted) are proposed. The accuracy of the proposed formula is proved by experimental simulation and real application scenarios, which provides an important theoretical basis for the study of the properties and key technologies of MANET topology. We only study the analysis of change of ASPL in MANET under random failures scenarios, without considering other topological characteristics, so we can analyze and study all kinds of topological characteristics in the next step. In addition, we do not deal with the changes of network structure after intentional attacks (destruction), with the difference of the intentional destruction strategy, there will be different impact.

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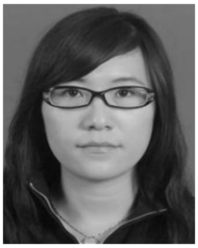

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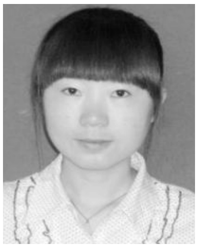

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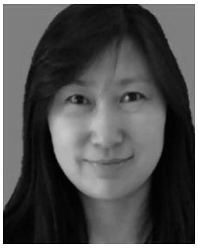

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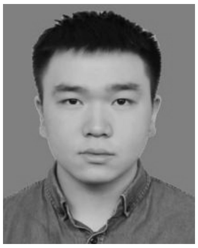

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