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Modeling and Mutation Evolution of IPv6 IP-Level Network Topology

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Abstract

In order to understand IPv6 topology characteristics and dynamic behaviors deeply, and guide the design of IPv6 Internet structure, an Internet IP level topology evolution model (IP-TEM) based on power-law distribution was established. Selected the data of IPv6 IP-level topology from CAIDA Internet Global Research Institute in the year from 2012 to 2016 to analyze the evolution characteristics of IPv6 during the probing period, and then introduced to the characteristic outlier weight to locate the mutation time point to analyze the network topology mutation evolution, it is concluded that the evolution trend of other characteristics and the mutation points of each characteristic outlier weight are basically the same except for the average clustering coefficient. Then simulated the normal evolution and mutation evolution of the network respectively using IP-TEM, the simulation results show that IP-TEM can simulate the normal evolution and partial mutation evolution of the real network.

Keywords

Internet Evolution, Topology Mutation, Characteristic Outlier Weight, IPv6

1. Introduction

Internet addressing, from the exhaustion of IPv4 address space to the leap to IPv6, the dimensionality of the IP address space is whipping up deployment storms around the world like a butterfly flapping its wings. The incremental deployment of address space (2^{128} - 2^{32}) will cause a series of changes in the future Internet, and IP addresses will lead to a revolution in the Internet address space [1]. Rather than the Internet generating a complex structure through changes in rules among many simple nodes, and the complex structure generating adaptive behavior, it is the interdependent but isolated nodes that collaborate to solve the survival problem by linking (Nexus).

As the Internet is a national resource, IPv6 is not only the deployment of new protocols, but also the cornerstone of next-generation Internet technologies such as Internet of Things (IoT), 5G, artificial intelligence (AI) and cloud computing. It also brings new opportunities to China and is the developing direction of China's network security and network sovereignty in the future [2] [3]. With the advent of the era of everything interconnection, IPv6 will take full advantage of its ability to provide 340 trillion (2^{128}) independent accesses to the Internet, which is a trillion times increase compared with the exhausted IPv4 address space (2^{32}), and IPv6 provides approximately 8000 trillion times more addresses than the IPv4 address space [4]. The dimension raising IP address has transformed the Internet from the ground up, and IP address will guide the deployment of emerging networks in the future [5].

In this paper, the topology data from 2012-2016 under CAIDA_Ark project is selected to analyze the topology evolution trend of IPv6 network, the characteristic outlier weight is introduced to choose the mutation time points. On this basis, the Internet IP-level evolution model based on power-law distribution is established to simulate the normal and mutation evolution of IPv6 network topology. An in-depth understanding of IPv6 topology characteristics and dynamic behavior is helpful to better design IPv6 Internet and optimize network topology.

2. Related Works

As early as in 1998, China built the first IPv6 test-bed, and launched China's Next Generation Internet (CNGI) project in 2003, marking the substantial development stage of IPv6 in China [6]. The Internet Corporation for Assigned Names and Numbers (ICANN) also officially approved the IPv6 prefix assignment policy in 2006, and by 2009, more than 300 North American Network Information Center (ARIN) members had been assigned IPv6 prefixes for IPv6 testing and early deployment. On June 6, 2012, the Worldwide Word Internet protocol IPv6 was officially launched worldwide, marking that the Internet is accelerating forward to the next network era. However, during the transition from IPv4 to IPv6, there are still compatibility problems between the two protocols [7] [8]. The Internet is a typical complex network, and its macro-topology exhibits extremely complex network characteristics [9] [10]. An urgent task is to conduct in-depth research on the structural characteristics, behavior and evolution activity rules of IPv6 network topology [11] [12] to lay out the network architecture reasonably and make accurate predictions on the future evolution of network topology.

At present, the development of IPv6 has entered the majority adopter stage, and how far it is from the mainstream of IPv6 technology has been a topic of concern. Zhang *et al.* [13] proposed network virtualization architecture of IPv6 to automatically provide virtual resources and abstract IPv6 transition services.

Yang *et al.* [14] established an evolution prediction model for IPv6 based on time sequences and hierarchical features, and simulated the IPv6 network topology evolution on this model to analyze and predict the evolution characteristics of its network topology. Ai *et al.* [15] used IPv6 IP-level topology modeling and simulation to identify anomaly evolution patterns of network topology. Wang *et al.* [16] delved into the Internet IP-level topology to measure network performance, and then proposed a method to improve the correct rate of link inference. Mahmood *et al.* [17] analyzed the neighbor discovery protocol in IPv6 and discussed the protection mechanism with aspects on the IPv6 security. Jia *et al.* [18] used historical BGP data and recent active measurements to analyze trends in the growth, structure, dynamics and performance of the evolving IPv6 and to compare them with IPv4 evolution. Previous studies have accumulated a certain amount of work in topology modeling and IP level data statistics, but most of them use the evolution characteristics of network topology feature quantities for evaluation and prediction. In this paper, characteristic outliers are taken as the starting point for research.

3. Data and Deductive Indicators

The IP-level topology is formed by extracting the network IP interfaces and links, and the data contains the original content of the network topology. In this paper, based on CAIDA_Ark probing data, taking month as the probing unit, IPv6 Internet IP-level data from 2012 to 2016 (a total of 60 months) are selected. Barabász *et al.* [19] have proved that the study using randomly sampling data replace of all data is reliable. Before analysis, the relevant definitions were as follows:

Definition 1. Average clustering coefficient [20]: it is the average value of clustering coefficient of all nodes in the network, *i.e.*, the network clustering coefficient. It is expressed by the formula below

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{1}$$

Definition 2. Average path length [21]: it refers to the average value of the shortest path length between any two nodes in the network, expressed by below

$$L = \frac{2}{N(N-1)}\sum_{i \geq j} d_{ij} \tag{2}$$

where d_{ij} is the shortest path length from node *i* to *j*. Average shortest path is an important indicator representing network communication capability and transmission performance. The smaller the value, the faster the information transfer.

Definition 3. Outlier [22]: it refers to a point in the sample space that is inconsistent with the general behavior or characteristics of other sample points.

There are various outlier mining algorithms. In this paper, a density-based local outlier mining method [23] is adopted to describe the mutation phenomenon of network topology characteristics in the process of Internet evolution, which is calculated as follows:

Step 1. The k-th distance of object p

For an actual data sample, the distance between object p and other objects are calculated firstly, finding the distance between object p and k, denoted as $k\text{-}distance(p)$, whose value is used to quantify the density of objects in the sample space. If the $k\text{-}distance(p)$ value is small, the density of the object is large. On the contrary, for the sample space with smaller object density, the $k\text{-}distance(p)$ value is large.

Step 2. The k-th distance domain of object p

The k-th distance domain of object p contains the sets of all objects (excluding p) whose distance from object p is not greater than $k\text{-}distance(p)$, denoted as $N_{k\text{-}distance(p)}(p)$. $N_{k\text{-}distance(p)}(p)$ may contain more than one object at the k-th distance, so the number of objects in the set is not less than k. Objects with higher outliers tend to have a larger range of $N_{k\text{-}distance(p)}(p)$, while objects with lower outliers tend to have a smaller range of $N_{k\text{-}distance(p)}(p)$.

Step 3. The reachable distance of object p with respect to object O.

The reachable distance is the one with the larger value of $k\text{-}distance(o)$ and $d(p,o)$, expressed as

$$reach\_distance(p,o) = \max\{k\text{-}distance(o), d(p,o)\} \tag{3}$$

Step 4. Local accessible density.

It refers to the reciprocal of the average accessible density of k nearest neighbors of object p, calculated by

$$Lrd_k(p) = \frac{N_k(p)}{\sum_{o \in N_k(p)} reach\_distance(p,o)} \tag{4}$$

Among them, $|N_k(p)|$ represents that the number of k-th distance domain of object p. From the formula $Lrd_k(p)$, it can be concluded that if the outlier degree of object p is small, there are likely to be $reach\_distance(p,o) = k\text{-}distance(o)$ among the objects in the same class cluster, and its $Lrd_k(p)$ value does not fluctuate much. Conversely, if the outlier degree of object p is large, then $reach\_distance(p,o) = d(p,o)$, the fluctuation range of $Lrd_k(p)$ value of the same class cluster object is also large, and $Lrd_k(p)$ value is also small.

Step 5. Local outlier factor.

It represents the outlier degree of object p, calculated by

$$LOF_{MinP}(p) = \frac{\sum_{o \in N_{MinP}(o)} \frac{Lrd_{MinP}(o)}{Lrd_{MinP}(p)}}{|N_{MinP}(p)|} \tag{5}$$

If the outlier degree of object p is small, the Lrd value of object O is close to that of object p, the resulting LOF value is close to 1. While if the outlier degree of object p is large, then most of the objects in its k domain are in the same class of clusters as the set of objects farther away from object p. Then the Lrd value of object p is smaller, and the Lrd value of object O is larger, and the resulting LOF value is larger.

Definition 4. Characteristic outlier weight: It is the outlier weights of some characteristics in time sequences are calculated by the definition of outliers and the density-based outlier mining method.

IP-level topology belongs to fine-grained classification category, IPv6 is still in the process of development, refining to each time sequences to calculate outlier weight not only reduces efficiency, but also has no substantive significance [24]. Therefore, in this paper, the density-based outlier mining method is improved, and the mutation extent of network topology evolution is illustrated using the resulting outlier weight value. The specific method is described as follows:

Step 1. Calculate the topological characteristics of the probing data in a certain period.

Step 2. Observe the changes of the calculated characteristics, and mark the time corresponding to the characteristics with obvious changes as outliers.

Step 3. The relatively flat detection data before and after the outliers were intercepted, and the outlier weight value of the topological characteristics after the jump is calculated, so as to judge whether the mutation occurred during the detection period.

Thus, the evolution process of Internet topology is divided into normal evolution and mutation evolution, which are defined as follows:

Definition 5. Topology mutation evolution: If there is a point in time when the outlier weight of characteristic is greater than 2 in a certain period of time, then a mutation in the topological evolution of the network has occurred in this local range.

Definition 6. Topological normal evolution: It refers to the evolution of other time ranges except mutation evolution.

4. IPv6 IP-Level Network Topology Evolution Characteristics

On the basis of maximum preservation of available information and stable functions, if new topologies can be generated quickly, then the entire network survives and develops stably, but the reality is often not so. With the increasing deployment and adoption of IPv6 protocol networks, the IPv6 network topology becomes more and more complex. As a result, the self-organization and self-replication evolution of the topology often abnormal, and errors are thus generated. Such self-replication evolution errors are called mutations. On the time sequences, the evolution trends of each network topological characteristic can be intuitively found by their jumping within a certain interval. Taking month as a probing unit in this section to analyze the changes of each topology characteristic in the growth process of IPv6 IP-level network topology from 2012 to 2016, and summarize the characteristics and rules exhibited by the network topology in the evolution process. Based on this, the timing evolution of the characteristic outlier weights is combined to analyze the mutation evolution of the IPv6 network topology during the probing period.

4.1. Evolution Characteristics of Global Attributes

To study the evolution characteristics of complex network in a certain time span, the statistical topology characteristics are usually used to analyze the basic attributes and network evolution trend by observing the statistical characteristics of each indicator. Taking month as a probing unit, the average network degree, average clustering coefficient and average path length from 2012 to 2016 (a total of 60 months) were calculated. The statistical results on each time sequences are shown in Figures 1(a)-(c). On this basis, each characteristic outlier weight is calculated, as shown in Figure 1(d). Each characteristic outlier weight is compared with the evolution characteristics of global attributes of the network topology to further analyze the mutation evolution of the IPv6 network topology.

Figure 1(a) shows the average degree of timing evolution of IPv6 network topology. During the 60-month probing period, the variation range of the network average degree was between 4.7 and 5.6. Except for a few months, the fluctuation of the network average degree in other months is small. Since the node degree describes the connection state between a node and its neighbors, the network average degree describes the connection characteristics of the entire network topology. The larger the average degree value, the higher the average

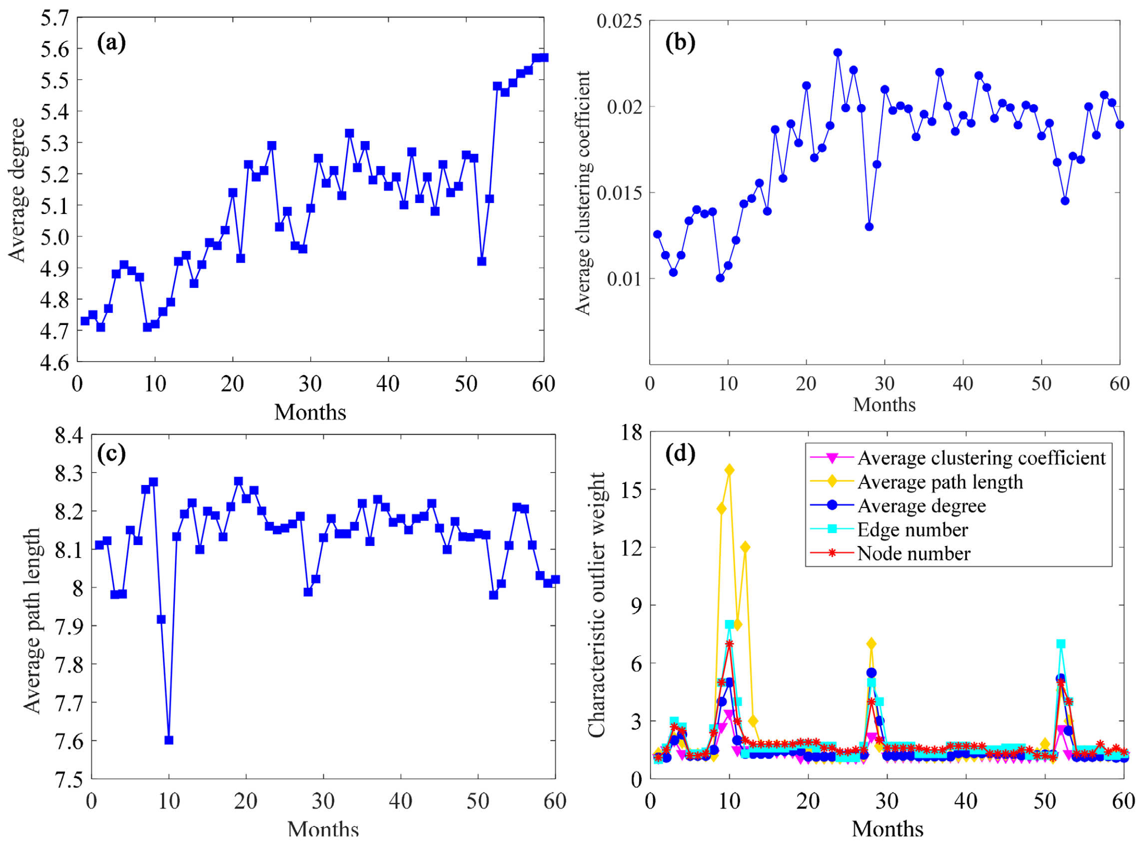

Figure 1. Timing evolution of IPv6 network topology characteristics. (a) Average degree; (b) Average clustering coefficient; (c) Average path length; (d) Characteristic outlier weight.

degree of network connection. From the figure, although the evolution of the average degree is timing oscillating, even with obvious jumps up or plunges in some months, the whole evolution trend is rising, indicating the increasing connectivity of the IPv6 network, the increased connectivity and robustness of the network, and the increasing self-healing ability of IPv6 for sudden changes in the network topology.

Figure 1(b) shows the timing evolution of the average clustering coefficient of the IPv6 network topology. The clustering coefficient describes the interconnected degree of neighbor nodes in the network topology. The higher the clustering coefficient of a node, the more connected edges among its neighbor nodes, and the path to that node has rich diversity. The average clustering coefficient reflects the clustering degree of the entire network topology. As can be seen from the figure, the average clustering coefficient slowly oscillates up and down within the first 20 months of the probe, and then tends to fluctuate up and down to a nonzero constant value, but the fluctuation range is small. The increase of the average clustering coefficient indicates that the connection relationship between neighbor nodes in the network is closer, which makes the network topology more complex, and it is difficult to control the self-replication error of the network topology. On the other hand, the tight connection makes the network topology more solid, which helps to cope with the negative impact of the topology mutation. Therefore, the higher the degree of network clustering is not the better. It is reasonable to stabilize the average clustering coefficient near a certain value in the evolution of network topology.

Figure 1(c) shows the timing evolution of the average path length of IPv6 network topology. If the self-replication behavior cannot quickly and accurately generate a new topology, the network performance will be directly affected, and the information transmission rate of the network will be reduced, and the communication capability of the whole network will be weakened. The average path length of the IPv6 network topology often fluctuates significantly in the evolution during the probing period, indicating that mutations often occur in the process of data transmission and that the stability of the IPv6 network topology is not high. This dynamic evolution also shows that IPv6 is better at adjusting its topology during self-replication activities and information transmission to provide high-quality services to the maximum extent.

From the analysis of the timing evolution of three conventional characteristics, it is found that the evolution of IPv6 network topology is not always smooth, and the oscillatory change of characteristics is its self-regulating behavior. Observing the timing evolution of statistical characteristics can only grasp the overall attributes and evolution trend of the network from a macroscopic perspective. According to definition 4, definition 5 and definition 6, the normal evolution and mutation evolution of network topology can be described intuitively by using the characteristic outlier weight, and the occurrence of topology mutations can be judged. Figure 1(d) shows the timing evolution of characteristic outlier weight of IPv6 network topology, and compares the outlier weights of node number and edge number. It is obvious from the figure that the characteristic outlier weights are less than 2 for most months during the probing period, indicating that the IPv6 network topology evolution is generally smooth, but the values of characteristic outliers jump sharply around the 10th, the 28th and the 52nd months, with the outlier weights of average path length, number of nodes and number of edges reaching their maximum values in the 10-th month, while the maximum values of outlier weights of average degree and average clustering coefficient appear in the 28-th month. Compared with **Figures 1(a)-(c)**, the average degree drops sharply in the 9th month and 52nd month, the average clustering coefficient drops sharply in the 9th month and 28th month, and the average path length drops to the lowest in the 10th month and 52nd month, which is basically consistent with **Figure 1(d)**. However, although the outlier weight of a certain characteristic at a certain time sequence point is the largest, there may be other objects with large changes, which do not indicate that mutation must occur. Therefore, in order to find the similar mutation time, it is not possible to focus only on the mutation of a single characteristic. Based on the above analysis, there are more than two characteristics with outlier weight larger than 2 in the third month, the ninth to the 7th month, the 28th - 29th month, and the 52nd - the 53rd month. Therefore, it is inferred that the IPv6 network topology has mutate d in these time sequences.

4.2. Evolution Characteristics of Topology Mutation

Based on the timing evolution analysis of the global attributes of IPv6 network topology and the outlier weights of each characteristic, the mutation points with the most correlation among each characteristic are extracted. As can be seen from **Figure 1**, the most obvious month is September to October, with the largest characteristic outlier weight values and the most associated characteristics. The detection time unit is refined to days, and the date is used as the horizontal coordinate and each characteristic indicator is used as the vertical coordinate to analyze the mutation evolution of network topology characteristics for these two months, as shown in **Figure 2**.

To analyze the growth process of a network, the evolution of the number of nodes and the number of edges is considered first, which together describe the scale of the network. **Figure 2(a)** & **Figure 2(b)** show the evolution process of IPv6 network scale, which spans from September 1 to October 30. It can be seen from **Figure 2(a)** that the evolution trend of the number of nodes is fluctuating up before September 21, with a small fluctuation range, and then rapidly decreasing to the lowest after September 29. The oscillation range of the evolution of the number of nodes in October is large, and then fall to the lowest around October 20. As seen from the evolution of the number of edges in **Figure 2(d)**, the evolution of the number of edges is relatively smooth until September 25, suddenly jumps and increases after that day, and continues to evolve with smooth fluctuations until about October 17, and then it plummeted to the lowest point around October 20. Comparing the evolution process of the whole time

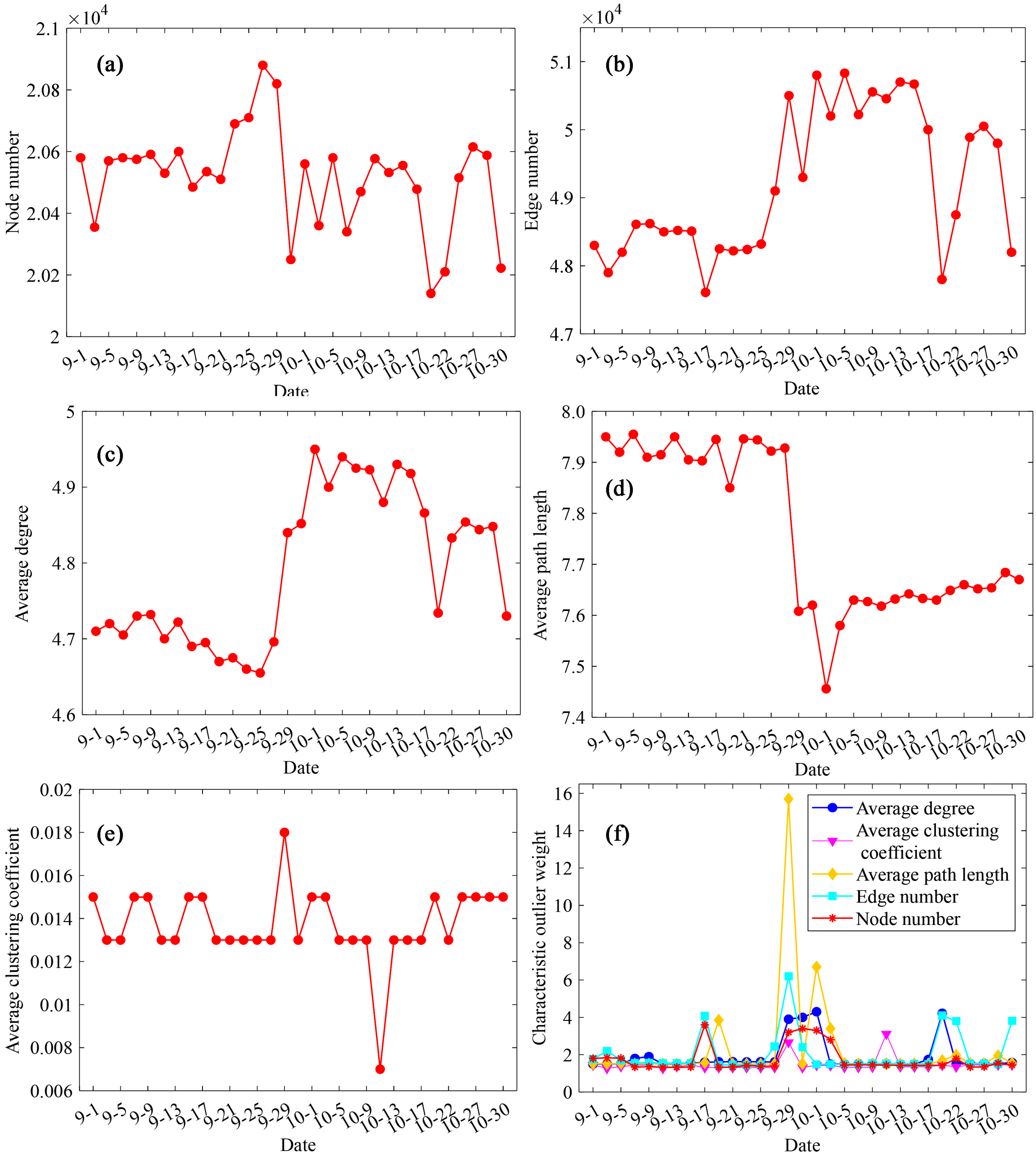

Figure 2. Mutation evolution of IPv6 network topology. (a) Node number; (b) Edge number; (c) Average degree; (d) Average path length; (e) Average clustering coefficient; (f) Characteristic outlier weight.

period, the number of nodes and the number of edges have a large range of evolution fluctuations, and their evolution states and trends are basically the same.

Figure 2(c) shows the evolution of the average degree. Since the average degree contains the information of nodes and edges, affected by them, the average degree value suddenly increases sharply at the time point of September 29, reaches the maximum value on October 1, and decreases sharply until around October 20. In comparison, the evolution trend of the average degree and the mutation time during the IPv6 evolution are roughly the same as the evolution of node number and edge number.

Figure 2(d) shows the evolution of the average path length. Before September 29, the average path length maintains fluctuating around 7.95, and then drops sharply on September 29, until October 1, when it reached the lowest level. After October 5, the evolution of the average path length is relatively stable, but the average path length in October decreases compared with that in September, indicating that the network topology changes when the network is attacked by external factors, that is, the connection relationship of the network is damaged and the data flow between nodes is affected to a certain extent. Therefore, the evolution trend of the average path length of the network is decreasing in the mutation period. However, in order to maintain the effective transmission of network information, nodes spontaneously seek other paths to transfer information among themselves, which manifests as smoothness after turbulence.

Compared with the evolution of the number of nodes, the number of edges, the average degree and the average path length, the evolution of the average clustering coefficient has been oscillating, as shown in Figure 2(e). It suddenly jumps to the maximum value on September 29 and plummets to the minimum value around October 10, and there is no smooth evolution transition during the whole period. This indicates that the clustering and connection states of nodes in the IPv6 network topology are extremely unstable in these two months.

Figure 2(f) shows the evolution of the outlier weights of each characteristic. From the figure, it is obvious that the outlier weights of more than two characteristics with values larger than 2 are concentrated around September 17, September 29 to October 1, and October 20, the most of which is September 29 to October 1. The outlier weights of each characteristic in these three days are very large, indicating the most serious network topology mutation. On September 17, only the network scale is abnormal, and then the average path length is affected, indicating that the change of network scale affects the network topology, and the structural mutation damages the network path. On October 20, just network average degree and number of edges mutate, that day the network connectedness is very low, other characteristics do not mutate, a possible reason is that although the IPv6 network topology is still unstable, but the evolution of average clustering coefficient is vibrating, prompting inter-node communication path changes, when the network connectivity will temporarily reduce, but not for long. It shows that IPv6 has strong robustness. Whether the network topology is mutated or some daily disturbances, IPv6 is good at making adjustments to deal with various abnormal situations.

5. IPv6 Topology Modeling Based on Power-Law Distribution

5.1. Model Establishment

IP-level topology evolution model (IP-TEM) is established based on the power-law distribution characteristics of Internet topology degree distribution [25], which is used to simulate the dynamic evolution of IPv6 network topology. The modeling process is as follows:

Step 1. Using the probing data as a sample, the degree distribution rates of each time sequences are calculated and fitted with the power-law in double logarithmic coordinates to obtain the fitting equation as below

$$\ln p(k) = A * \ln k + B \tag{6}$$

where, k is degree value. Let $maxdegree$ is the largest value, then it has $0 < k \leq maxdegree$, $p(k)$ is the degree distribution. A is the power-aw coefficient, B is the intercept.

Step 2. It can be deduced from Equation (6) as below

$$p(k) = k^A * e^B \tag{7}$$

Using Equation (7) to calculate $p(k)$ when k is from 1 to $maxdegree$, and then save them.

Step 3. The number of network nodes is multiplied by $p(k)$, and the result rounded is the number of nodes with k degree value. The number of nodes with corresponding degree value is calculated by the same method. If the rounded value is 0, then $p(k)$ is accumulated and added until it is non-zero, so that it has the long-tail feature. Let the degree value be the attribute value of the node, and the weight of the node is initialized to the degree value. The weight will decrease with the number of edges connected to the node.

After the calculation of Step 1, Step 2 and Step 3, the node set on $1 \sim maxdegree$ can be obtained, and the IP-TEM modeling with the algorithm process as shown in **Figure 3** is carried out for them. Let the number of nodes in the original network is m_0, weights are randomly assigned between 1 and 20.

5.2. Mutation Evolution

Assuming that the original network *Origin* has a certain scale, the algorithm flow of mutation evolution is shown in **Figure 4**, described as follows:

Step 1. The information of born nodes and dead nodes are stored in *born. txt* and *dead. txt* respectively. The two documents contain the number of nodes and their degree values.

Step 2. Read *born. txt* and *dead. txt* at the point in time when the mutation is triggered, they can cause the mutation.

Step 3. Based on the information in *born. txt* and *dead. txt*, the nodes in the local network at a time point before the mutation are deleted, and the weight of its neighbor nodes is added by 1, and the number of nodes with corresponding degree value in *dead. txt* is subtracted by 1. Then, a node with *maxdegree* is added in this local network according to the information in *born. txt*, and the number of corresponding nodes is subtracted by 1 in *born. txt*, nodes are added with edges in the same way as new edges are generated in IP-TEM modeling.

Step 4. Repeat Step 3 until the number of nodes with corresponding degree

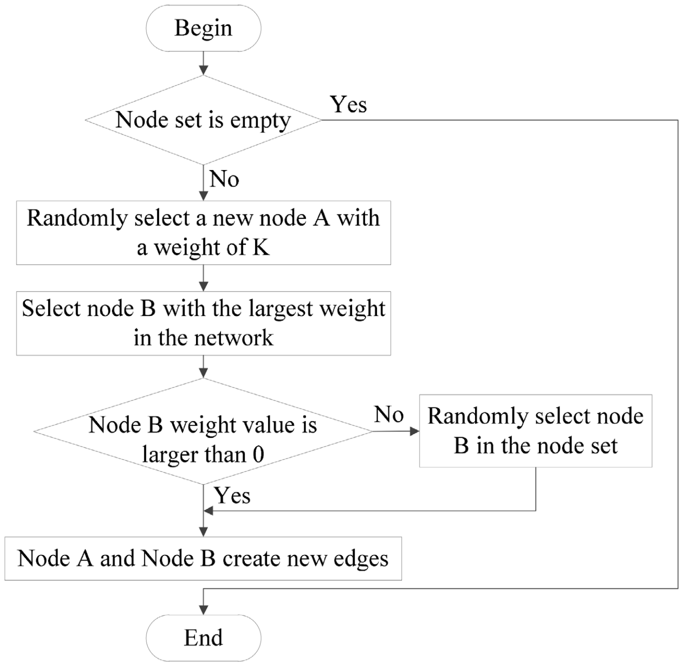

Figure 3. IP-TEM modeling process.

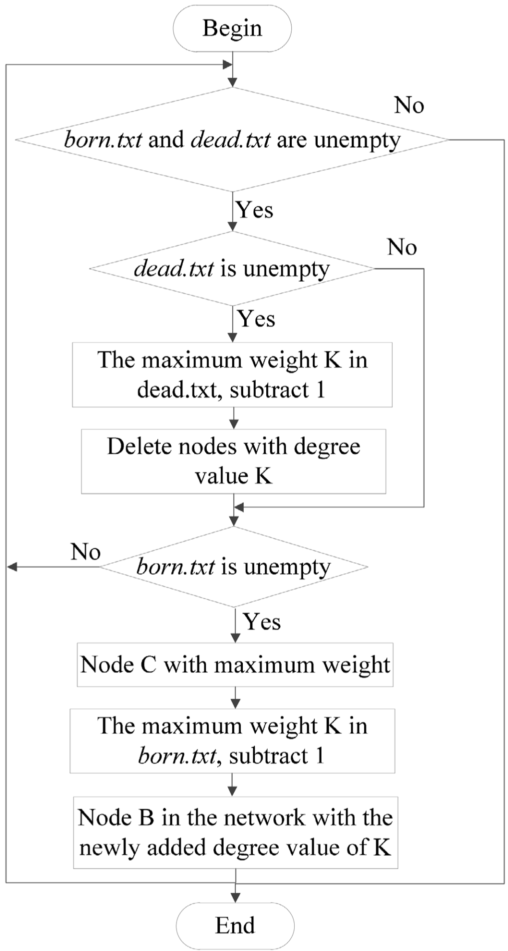

Figure 4. Mutation evolution algorithm process.

values in the two files is 0.

5.3. Normal Evolution

Let the initial state of the original network *Origin* has a certain scale. For the dead nodes, they are deleted along with all edges directly connected to them, while the weight values of all neighbor nodes are added by 1. For born nodes, each node also has a certain weight. If the weight of the new node is M, the N nodes with the largest weight are selected from the network, which satisfies $N(0 < N \le M)$. If the weight of nodes in the network is less than 0, N nodes are randomly selected. The algorithm process is shown in Figure 5.

5.4. Model Evaluation

IP-TEM model is based on power-law distribution. In order to verify its power-law characteristic, a network with 9404 nodes is generated according to IP-TEM modeling algorithm, and the IPv6 IP-level network topology data of July

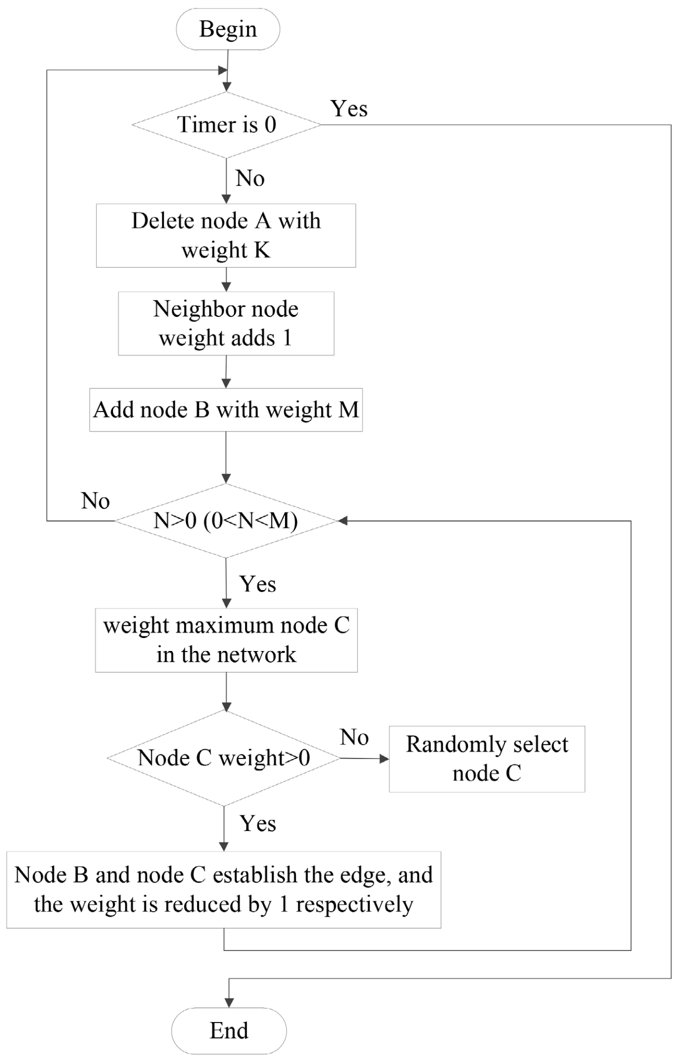

Figure 5. Normal evolution algorithm process.

2016 is selected as the prototype. AB [26], BA [27], CBEN [28] and IP-TEM are used to construct networks of the same scale. The network degree distributions of the four models are compared, as shown in **Figure 6**.

The figure shows the IPv6 IP-level topology, IP-TEM model, BA model, AB model and CBEN model network degree distribution in double logarithmic coordinates. The degree distribution generated by IP-TEM model has a long-tail characteristic. Compared with IPv6, the degree distributions of the four model networks can basically coincide with that of IPv6, and there is a slight difference in the low degree value, indicating that the degree distribution of the entire network topology is in line with the power-law characteristic. IP-TEM model can effectively simulate the degree distribution characteristics of Internet IP-level topology. The network constructed by the four models is simulated for 20 times and compared with the actual IPv6 IP-level network topology characteristics. The results are listed in **Table 1**.

From the comparison of each characteristic in the table, when the node number is roughly equal, edge number, average degree, maximum degree and power-law coefficient of the network topology generated by IP-TEM model are closer. Therefore, whether in terms of network scale, connectivity, communication rate, etc. are very close to the actual network, the formation mechanism of

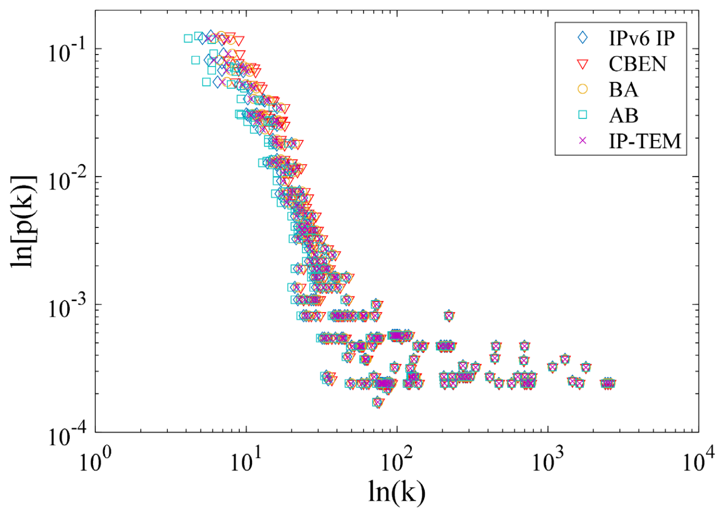

Figure 6. Comparison of degree distribution between IPv6 IP-level topology and model network.

Table 1. Comparison of basic characteristics of each model.

Characteristics	IPv6 IP	BA	AB	CBEN	IP-TEM
Node number	9406	9406	9405	9411	9404
Edge number	20,669	14,128	17,988	17,989	20,503
Power-law coefficient	2.07	1.73	2.55	1.82	2.0
Average degree	4.775	2.899	3.879	3.94	4.417
Maximum degree	322	280	225	286	317

IP-TEM model is basically consistent with the reality.

6. Evolution Simulation

6.1. Simulation of Normal Evolution Process

Intercept the time period when the evolution trend of the network topology characteristics on the time sequences is relatively flat. From the analysis in Section 4.2, the evolution of each characteristic is relatively stable from September 1 to September 16, and the probing data at corresponding time points can be used as original data samples for the normal evolution of Internet topology. According to the description of the dynamic evolution process of IP-TEM algorithm, the normal evolution of IPv6 network topology is simulated. The IP-TEM model is simulated and evolved for 30 times. As the IP-TEM model added the factors of node birth and death in the modeling process, the new nodes and death nodes are taken as the entry point in the evolution simulation, and the network generated 1 - 5 new nodes and death nodes in each simulation. At the same time, the condition is that the difference between the degree values of the new node and the dead node is not greater than 1. The evolution effect of each characteristic is shown in **Figure 7**.

As seen in the figure, after several evolutions, the individual characteristic in the IP-TEM model does not show significant fluctuations. The evolution of node number is relatively flat, the evolution of edge number and the average degree show a slow upward trend, while the average path length and the clustering coefficient show a decreasing trend, probably because although the topology connectivity of the network gradually increases, the connections tend to be more randomly connected, making the network less agglomerative. Further observe the changes of outlier weight in the node number, edge number, average path length, average degree and average clustering coefficient during the 30 times evolutions. According to the definition of topology mutation, the time point whose outlier weight value of characteristic is greater than 2 is regarded as the mutation point. However, the outlier weight values of each characteristic in the figure are all below 1.4, which again indicates that the evolution of each characteristic does not fluctuate greatly and the network topology does not mutate. IP-TEM model is relatively accurate for the normal evolution of network topology.

The stable evolution of the network indicates that the growth and development of the network are relatively stable in a period of time. However, the structure and performance of the network are not always in optimal condition. From the perspective of the evolution of each characteristic, the decline of the evolution trend of the average path length is beneficial to the development of the network to a certain extent, which can accelerate the information transmission rate of the network, and the gradual increase of the average degree indicates that the connectivity of the network is becoming stronger and stronger. The possible reason for the opposite evolution trend of the two characteristics is that the IP-TEM model simulates the normal evolution of the network by constantly

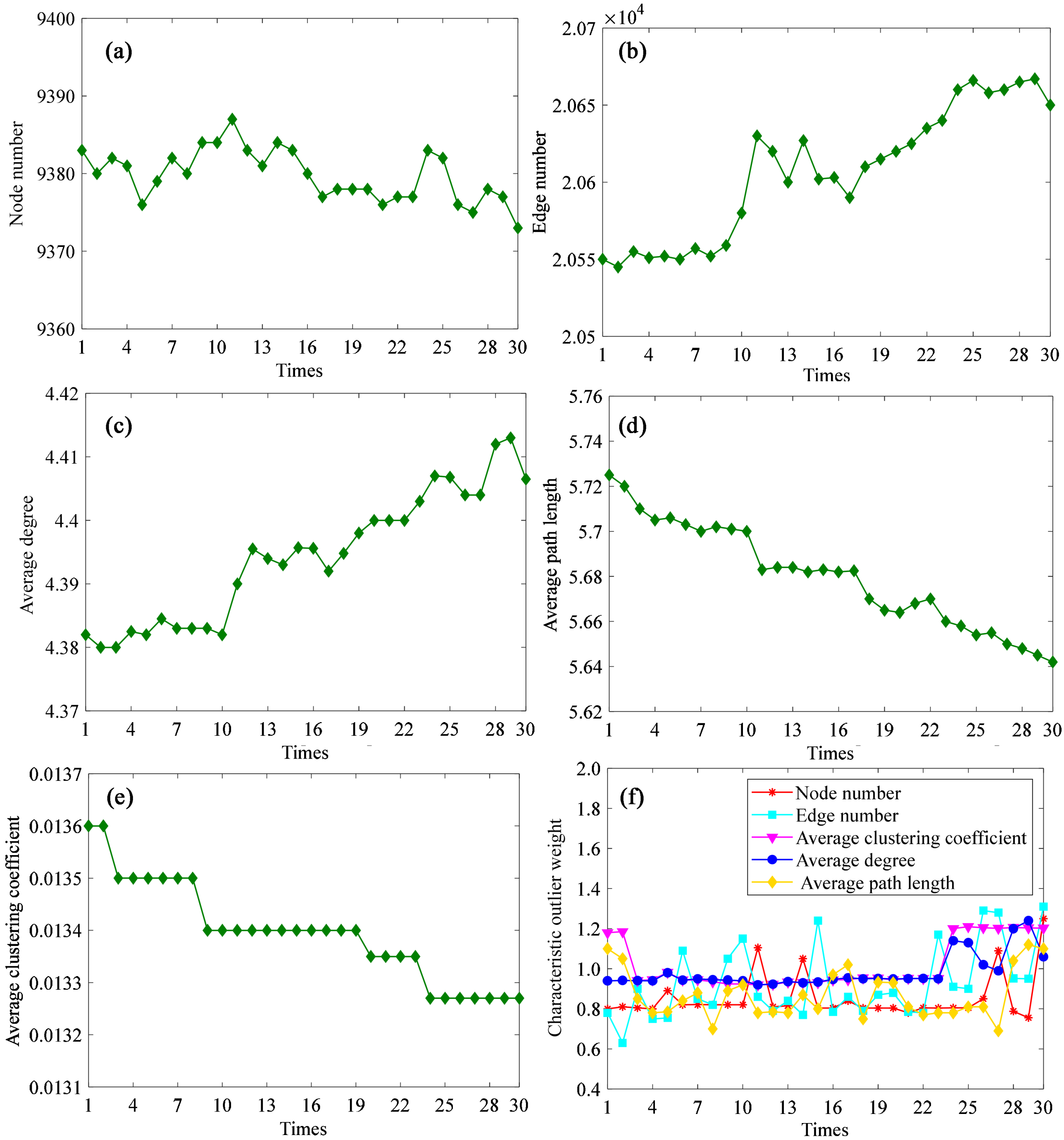

Figure 7. Normal simulation evolution of IP-TEM model. (a) Node number; (b) Edge number; (c) Average degree; (d) Average path length; (e) Average clustering coefficient; (f) Characteristic outlier weight.

adding (born) and deleting (dead) nodes, which makes the edge nodes have the opportunity to connect with the center nodes, resulting in the reduction of the average path length of the network. The different connection modes of edges directly affect the network structure. The decrease of network clustering coefficient means that the paths between nodes in the network are reduced, and the routing performance in the network is reduced, which is disadvantage of the network development. From this point of view, while applying the IP-TEM model to analyze the normal evolution of the network topology, it is also necessary to combine the evolution trend characteristics of each network topology characteristic to gain insight into the internal structure of the network topology under normal state.

6.2. Simulation of Dynamic Evolution Process

From the analysis in Section 4.1, the evolution of IPv6 network topology during the probing period is relatively stable except for the third month, 9^{th} - 11^{th} month, 28^{th} - 29^{th} month, and 52^{th} - 53^{th} month. The most obvious mutation is in September and October. In Section 4.2, the topology mutation characteristics of these two months are analyzed, and the specific mutation time points are located around September 17, September 29 to October 1, and October 20. Only analyzing the change of the network topology characteristics at the mutation time point cannot accurately understand the evolution rules of the network. It is necessary to compare the network topology characteristics before and after the mutation point, so that the analysis of the mutation evolution of the network topology in a continuous period of time including the mutation point is comprehensive. Therefore, the topological data of September and October are still intercepted as mutation samples to analyze the network mutation evolution of each characteristic during the evolution of IP-TEM model.

Firstly, IP-TEM model is used to generate data samples of the same scale as the original data. On this basis, the IP-TEM model is simulated and evolved for 30 times. The simulation results are shown in **Figure 8**.

As can be seen from the figure, after several evolutions, the evolution of the node number, edge number, average degree and average path length show many large jumps, while the evolution trend of the average clustering coefficient is flatly declining. The evolution trend of node number and edge number is basically the same, which is consistent with the evolution of IPv6 network scale. Only the evolution of the outlier weight of the node number can be simulated. However, by comparing the mutation evolution of the actual network topology in Section 4.2, except the evolution of node number is consistent with that in **Figure 2(a)**, the mutation evolution of other characteristics is not completely consistent with the corresponding evolution graph of characteristics in **Figure 2**, mainly reflected in the jump of mutation points. Compared with the evolution trend of edge number, average path length and average clustering coefficient in the actual IPv6 network topology, the simulating evolution with upward or downward jumps is not synchronized with (**Figure 2(b)**, **Figure 2(d)**, **Figure 2(e)**), some appearing jumps while in the actual network is flat, some upward jumps while in the actual network evolution is downward, or even the lowest. The frequent oscillation of average degree is also inconsistent with **Figure 2(c)**. One reason for the above phenomenon is probably the dynamic change between the born node and the dead node. The birth nodes and death of nodes affect

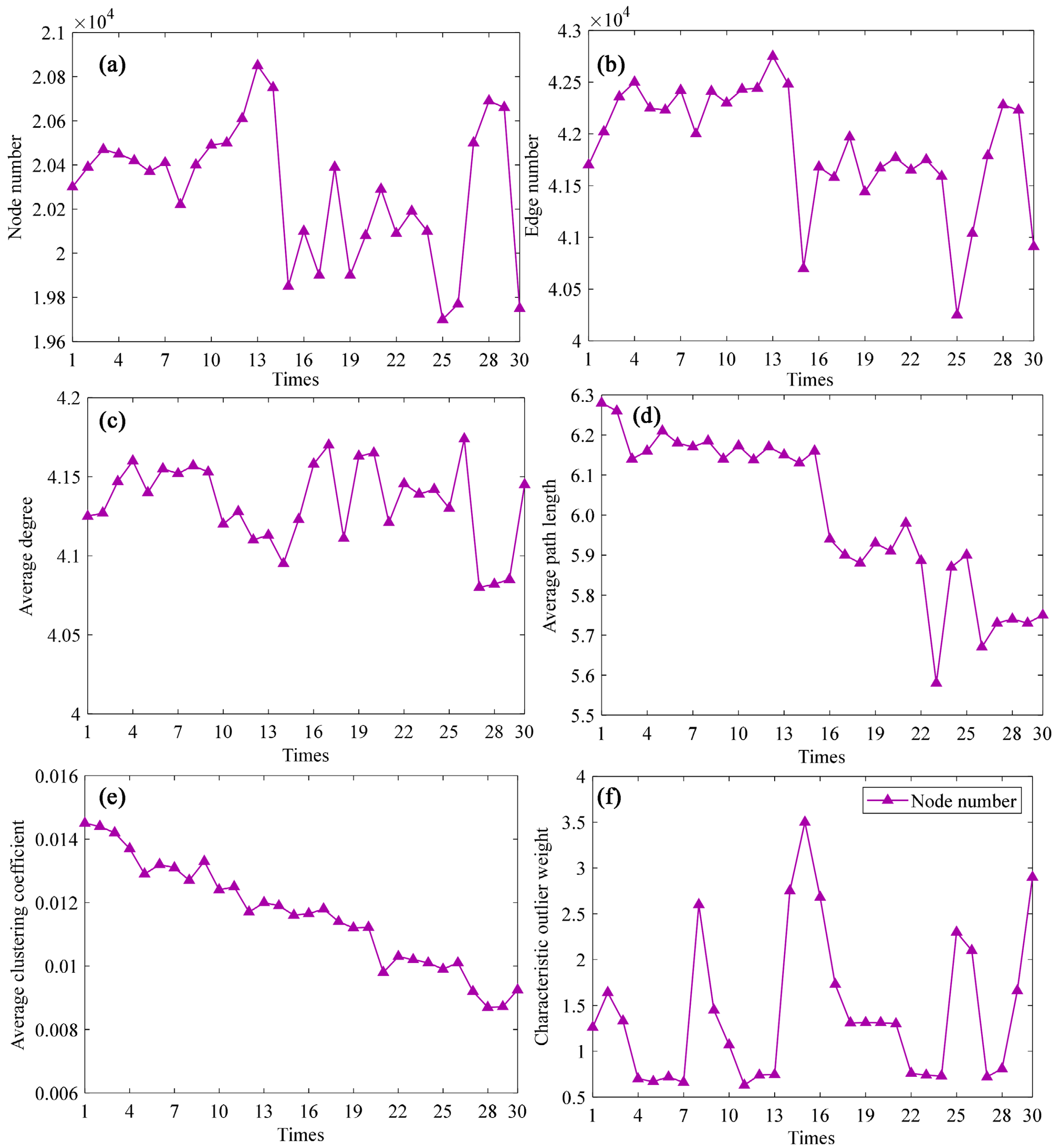

Figure 8. Mutation simulation evolution of IP-TEM model. (a) Node number; (b) Edge number; (c) Average degree; (d) Average path length; (e) Average clustering coefficient; (f) Characteristic outlier weight.

their degree distribution. The sample data of IP-TEM model is static, and the degree distribution of network is fixed. In contrast, during the evolution of the actual IPv6 network topology, the degree distribution of nodes is dynamically assigned, which makes the simulation results inaccurate. The evolution of each network topology characteristic is not independent, whether it is normal or mutation evolution, and a single characteristic mutation does not indicate that the network topology occur the mutation at that point in time. The complexity of the actual network topology makes its evolution characteristics cannot be explained by a single factor, and the IP-TEM model proves this assertion.

7. Conclusions

Based on the IPv6 IP-level topology data from 2012 to 2016, this paper firstly analyzes the evolution characteristics and trend of IPv6 network topology, and concludes that the global attributes of the network during the probing period are oscillatory evolution, and there are abnormal jumps of characteristics in similar months. On this basis, the characteristic outlier weight is introduced to judge the mutation time of the network topology evolution, and the mutation point can be accurately located by combining the two methods. Then the network topology mutation evolution is analyzed, and the evolution trend of each characteristic and the mutation time are approximately the same except for the average clustering coefficient, and the mutation time point is further determined. After that, the Internet IP-level topology evolution model (IP-TEM) based on power-law distribution is established, and the algorithm flow of normal evolution and mutation evolution of network topology is established. The static effectiveness of IP-TEM model is verified by comparing it with other models and real topology characteristics. Finally, in IP-TEM model, birth and death factors are added to simulate the normal evolution and mutation evolution of IPv6 IP-level topology, respectively. The simulation results show that the IP-TEM model can simulate the normal evolution of the actual network and the evolution trend of the network scale mutation. The other evolution characteristics should be analyzed to fully understand the network topology mutation. The IP-TEM model proves that a single characteristic mutation cannot fully explain the network mutation.

In the future, the measurement range of topology characteristic mutation will be extended to all the t topology characteristics, and the internal law of each characteristic mutation will be studied. On this basis, combine the mutation law of different characteristics should be tried to achieve the simulation of the mutation phenomenon in the real topological network by adjusting the single factor.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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