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A High Completeness PoP Partition Algorithm for IP Geolocation

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ABSTRACT Point of Presence (PoP) composed of routing nodes with specific connections can reflect structural properties of a local target network, which can be used for capturing the network dynamics and geolocating target IPs. However, PoP with low completeness may cause the failure of existing PoP-based IP geolocation methods. In this paper, a high completeness PoP partition algorithm for IP geolocation is proposed. Unlike some traditional PoP partition methods that directly use non-backbone routing nodes to obtain PoPs, this paper applies iterated subnet analysis to PoP partition of a specific area. Other IPs that are hosted on the same subnet which accommodates each node are acquired; a novel strategy is designed based on the similarity of routing hops and single-hop delays to filter non-regional IPs, and more new non-backbone nodes are acquired using probed results of the remaining IPs; the steps above continue to be applied iteratively to these new nodes and the iteration is aborted until almost no new nodes can be acquired. Alias resolution is introduced into this algorithm and tightly connected network structures (Bi-fan) are extracted to obtain final PoPs. The location attribute of PoPs are determined according to the locations of corresponding landmarks whose probed paths pass through the PoPs, thus these PoPs can be used to geolocate target IPs. Principles analysis and experimental results of some areas in China and the USA show that, compared with existing typical algorithms like PoP-Geo, PoP-NTA, and CRLB, PoPs obtained by the proposed algorithm are more complete and can significantly improve the success rate of geolocating target IPs.

INDEX TERMS PoP partition, IP geolocation, Bi-fan structure, subnet analysis, alias resolution.

I. INTRODUCTION

At present, more and more network devices such as routers and switches are connected to the Internet. The network scale is expanding and the topology is becoming more and more complex [1], [2]. PoPs often have strong geographical attribute and can reflect the evolution of the Internet. A high completeness PoP means that it contains as many nodes as possible so that can reflect the structure of the PoP in a real network. In a PoP-level network, each PoP consists of a large number of closely connected routing nodes, which are often located in a certain city and serving users' terminal hosts, with obvious city-level regional attribution characteristics [3]. When probing IPs in a certain city, the routing paths often pass through the PoP of the city and then reach destination IPs. Therefore, according to this characteristic of PoPs, conduct research on the method of PoP networks partition in specific areas is of great significance for practical applications such as acquiring the regional PoP-level network topology, understanding the regional network structure characteristics, capturing the regional network dynamics [4], detecting important nodes in the network and determining specific target IPs' city-level position *etc*. [3], [5]–[7]. In addition, the use of PoPs for target IPs geolocation can greatly improve the success rate of geolocation methods that based on landmarks, and reduce the dependence on the number of landmarks [8]–[10].

In terms of PoP-level network analysis, existing researches have studied based on router domain names, network delay characteristics and special structures (such as a Bi-fan structure) included in the network. Spring *et al*. [11] analyze a large number of routing nodes' probed results and find that

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some routers' domain names imply location information. For example, the domain name "s1-bb11-nyc-3.0.sprintlink.net" represents a router which belongs to the Internet Service Provider (ISP) named "Sprint" in New York City ("nyc" is the abbreviation of "New York City"). This feature is used to divide routers with the same position characters in domain names into the same PoP. This method can be used for PoP partition to some extent. But router domain names are usually difficult to obtain and their naming rules are not standardized. So PoP partition method based on the routers' geographical location information inferred from characters in domain names is unreliable. Based on [11], Madhyastha *et al.* [12] propose the algorithm named "iPlane", which uses the open data source "Rocketfuel", "Sarangworld" and assigns domain names to as many routing nodes as possible. Routers with the same location indication characters in domain names are further probed and the ones which have similar probed paths and routing information are divided into the same PoP.

Feldman *et al.* [13] analyze the network structure of a PoP and point out that nodes in it are geographically close and tightly connected. So delays between nodes in the same PoP should be relatively small. For the probed paths, the algorithm analyzes and extracts every routing link whose single-hop delay is lower than the threshold and corresponding nodes, constructs candidate node sets and finishes the partition of PoPs by merging these sets. On the basis of [13], Feldman *et al.* [14] extend the algorithm and propose PoP-Geo (PoP Geolocation). The algorithm gives the estimated position of each PoP. Liu *et al.* [15] propose PoP-NTA (PoP-level Network Topology Analysis). They extract PoPs from the network topology and also give estimated locations of PoPs.

PoPs obtained by methods mentioned above can geolocate target IPs to some extent. However, when the number of landmarks is not sufficient or some of them are inaccurate, the locations of PoPs with low completeness based on these landmarks may be wrong. These PoPs will geolocate Target IPs incorrectly. Taken to an extreme, when the number of landmarks is very small, locations of some small-scale PoPs are uncertain, so target IPs locations cannot be given by these PoPs. Target IPs geolocation will fail under these two circumstances. So it is necessary to improve the completeness of PoPs that the failure rate will be reduced when using PoP to geolocate target IPs.

Aiming at problems mentioned above, this paper proposes a high completeness PoP partition algorithm for IP geolocation. Through the proposed algorithm, PoPs with high completeness can be obtained, which can greatly improve the success rate of target IP geolocation. The contributions of this paper are as follows:

- A high completeness PoP partition algorithm based on subnet iteration analysis is proposed. By the excluding of backbone routing nodes, the iteration of subnet analysis, and alias resolution, a large number of non-backbone routing nodes without aliases are obtained, and PoPs with strong urban attribution as well as high completeness are extracted.
- Principles of the proposed algorithm are analyzed and verified by different experiments such as PoP partition and target IPs geolocation. Results show that the proposed algorithm can reduce the dependence of the IP geolocation methods on the number and accuracy of landmarks, and can still successfully geolocate target IPs when IPs are unreachable in some cases. This may not be possible with some traditional geolocation methods.

The rest of this paper is organized as follows. The PoP network and existing two typical partition algorithms are introduced in Section II. Section III mainly introduces basic principles and main steps of the proposed algorithm. The principles are analyzed in Section IV. In order to verify the effectiveness of the proposed algorithm, in Section V the two typical algorithms introduced in Section II and the proposed algorithm are used to conduct PoP partition experiments in Henan, China and Florida, US. The PoP partition results are used to conduct city-level geolocation tests on IPs in the two areas and the geolocation results are analyzed to further illustrate the effect of the proposed algorithm. Finally, Section VI summarizes the full text and points out the problems of this paper and the future research directions.

II. RELATED WORK

In this section, the PoP-level network is briefly introduced from the aspects of network structure and geographical distribution characteristics. Then, the existing two typical PoP partition algorithms are briefly analyzed and the problems involved are pointed out.

A. INTRODUCTION OF POP-LEVEL NETWORK

According to the networks divided by different granularities, there are roughly many kinds such as IP-level, AS-level network and so on. Among them, the PoP-level network is one of the most important ones. Usually, ISPs would like to place a large number of routers that tightly connected in a specific city [14]. A PoP is composed of these routers. So in

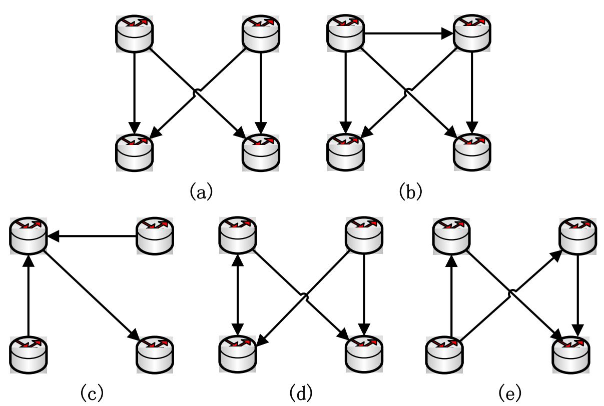

FIGURE 1. Common ways of network node connection in complex networks.

a PoP-level network, each PoP is usually belongs to a certain city, which serves the corresponding city [3]. As the IP-level network that is too granular, the AS-level network that each AS spans multiple countries even multiple continents and is too coarse-grained, these two kinds of network are of little help to network analysis of specific local areas like cities. Instead, the PoP-level network gives a better level of aggregation. So it is suitable for studying the Internet evolution and city-level topological analysis in a specific province or state. More importantly, the urban attribution of a PoP makes it available for city-level geolocation of specific target IPs.

There are roughly five ways to connect routing nodes in the complex network environment as shown in Fig. 1. Milo *et al.* [16] conducted a large number of statistical analysis on these basic network structures and found that the network structure shown in Fig. 1(a) (*i.e.*, the Bi-fan structure) has the strongest connectivity and representativeness. A PoP is composed of a large number of Bi-fan structures that with common nodes. These nodes in it are all routing nodes that are geographically close and often located in the same area (usually in the same city), responsible for data transmission and exchanging [17], [18].

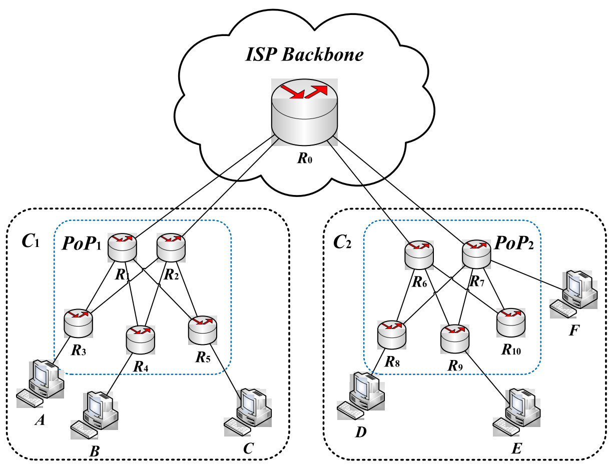

FIGURE 2. Schematic diagram of a PoP network.

A city usually contains one or several PoPs, but a PoP is often located only in a certain city. As shown in Fig. 2, PoP_1 and PoP_2 are PoPs composed of a plurality of Bi-fan structures, and the two belong to the city C_1 and C_2, respectively. The hosts A, B, C, D, E, and F will connect to the ISP backbone network through PoP_1 and PoP_2 to implement data interaction between each other.

B. INTRODUCTION AND ANALYSIS OF TWO TYPICAL POP PARTITION ALGORITHMS

Feldman *et al.* [14] propose PoP-Geo (PoP Geolocation) for PoP partition and geolocation within an AS. The probed results from multiple vantage points are analyzed according to the tightly connected structural characteristics of the PoP network. Nodes are divided into different connected components according to single-hop delays between them and the number of times that probing packets transmitted between them. Bi-fan structures are further found within a connected component and are further merged to obtain PoPs in accordance with whether there is at least a common node between them as well as the delay value of a link. Databases are used to determine the locations of nodes in each PoP,

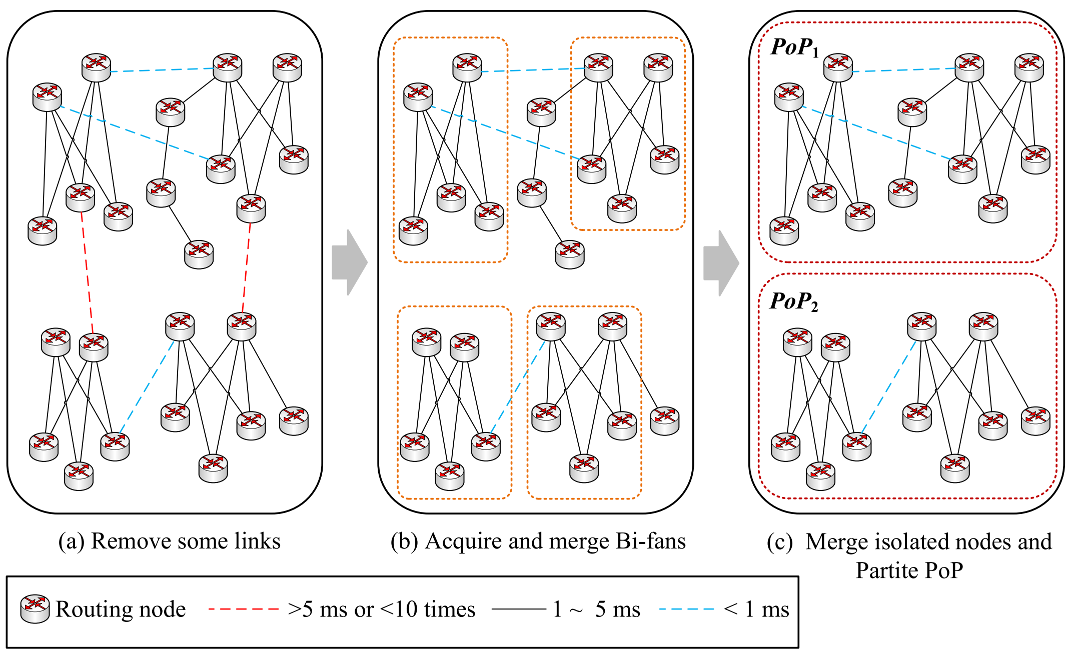

FIGURE 3. Schematic diagram of the algorithm.

and then the location of each PoP is obtained based on a voting mechanism. The principle of the algorithm is shown in Fig. 3 and the main steps are as follows:

1) Initial partition. An existing distributed detection framework called "DIMES" is used to probe IPs in an AS from multiple sources to obtain an IP-level topology. The IP-level topology is further processed as shown in Fig. 3(a). All links with delay values higher than the maximal threshold 5 *ms* or with the number of probing below the minimum threshold 10 are removed. After that, the IP-level topology is divided into multiple connected components and each one will contain one or more PoPs.

2) Refined partition. As shown in Fig. 3(b), look for Bi-fan structures within each connected component and merge them into a group. If there is at least a common node between any two groups or the link' delay value between groups is less than 1 *ms*, the two groups are further merged. As shown in Fig. 3(c), the remaining isolated nodes are divided into groups with a distance of 1 to 2 hops. The final merged groups are taken as the PoP partition result in the AS.

3) PoP geolocation. Query multiple geolocation databases to obtain locations of nodes in each PoP. The location of each PoP is obtained by using a voting mechanism according to locations of nodes.

Liu *et al.* [15] propose PoP-NTA (PoP-level Network Topology Analysis), a PoP partition algorithm based on Bi-fan structures extraction. The main steps of the algorithm are as follows: 1) a small number of IPs and landmarks in the area are selected and probed; 2) probed paths are analyzed to obtain the topology and routing nodes of the area; 3) Bi-fan structures are extracted and merged to obtain PoPs according to routing nodes and links in the area; 4) the city-level position of each PoP is given according to probed data of landmarks.

The geographical distribution characteristic of PoPs as well as the links and delay characteristics between nodes in each PoP are analyzed. The PoP partition are performed using the above algorithms. It is found that the two algorithms have the following problems.

1) PoPs obtained contains too many backbone nodes and their urban attribution are weak. When using PoP with weak urban attribution for IP city-level geolocation, incorrect geolocation results are often given. An AS geographically spans a large range. Many ASs span multiple countries and even multiple continents. PoPs for an AS contain too many backbone nodes. These nodes are sparsely distributed and distances between them are relatively long. The geographic coverage of a PoP is too large and the granularity is coarse. The city-level locations of these PoPs is uncertain. Through these PoPs with weak urban attribution, the accurate city-level locations of target IPs may not be obtained.

2) PoPs obtained are always not complete enough. These PoPs may not be able to give locations of target IPs. The main reasons are as follows:

- IPs to be probed are often obtained by the relevant geolocation databases. However, existing researches have pointed out that the location information given by different databases to the same IP is inconsistent. The reliability of result from a single database is difficult to guarantee [19], [20]. The number of IPs with consistent location information from multiple databases is limited. This makes it difficult for algorithms above to obtain and probe as many IPs as possible in a specific area. The number of routing nodes and links obtained in an area is small. A large number of non-backbone routing nodes have been omitted. As a result, the completeness of each PoP is low.
- Alias resolution is not performed before Bi-fan structures merging and PoPs partition. Routers often have multiple interfaces, each of which is configured with a different IP address. Aliases are different interfaces on the same router. During multiple probes, packets may enter from different interfaces of the same router and be forwarded from different interfaces to other routers. Before the PoP partition, if aliases are not merged, interface IPs belonging to the same router are often regarded as different routing nodes in the network topology. Routing nodes in a city that belong to the same PoP are divided into multiple ones with a small scale. These smaller PoPs are not complete.

III. THE PROPOSED ALGORITHM

A large number of probed data as well as the characteristics of network delays and structures are analyzed. Based on network characteristics such as the "low-high-low" distribution characteristic of single-hop delays in paths [13], the city-

Algorithm 1 The High Completeness PoP Partition Algorithm

Input: 1. An IP set T to be probed for a specific area. In particular, IPs in T should cover cities in the area as many as possible to ensure that the PoP of each city in the area can be obtained;
2. A landmark set L used to determine the locations of PoPs obtained.

Output: The final PoP partition result R, in which each PoP is of high completeness and the position is determined.

Main steps:

1: Multi-source probing for IP_i in T. Lots of vantage points are distributedly deployed across many areas and the tool called "traceroute" is leveraged to send many kinds of probing packets to probe any IP_i in T for many times. At the same time, probe the landmarks in L.

2: Obtain the probed path $Path_i$ of IP_i in T.

3: According to the "low-high-low" distribution characteristic of single-hop delays between adjacent routers, $Path_i$ is divided into $Path_{outside}$ and $Path_{inside}$.

4: Obtain regional routing nodes to construct the set S from all the $Path_{inside}$.

Algorithm 1 *(Continued..)* The High Completeness PoP Partition Algorithm

5: According to the routing hop count u_i and each single-hop delay v_{ij} in $Path_{outside}$, construct the HDV_i (Hops-Delay Vector, hereafter HDV) forIP_i and a reference HDV_{ref} for each city in the area that used to filter IPs not in the area.
6: According to the city-level location consistency of subnet IPs, perform subnet analysis on any routing node in S and obtain other IPs that belong to the same subnet to construct the set S_{subnet}.
7: According to the similarity of routing hop count and single-hop delay in probed results of IPs in the same city, calculate the Euclidean distance betweenHDV_{ref} and HDV_i of each IP in S_{subnet}.
8: Determine whether any IP_i in S_{subnet} belongs to the specific area according to the distance value. Exclude very few subnet IPs that are not in the area and then construct the set $S^{'}_{subnet}$.
9: Obtain new routing nodes to construct *temp* using all $Path_{inside}$ of IPs in $S^{'}_{subnet}$. If the number of new routing nodes in *temp* is large, that is, lots of new routing nodes still can be obtained, then let $S \leftarrow temp$, return to step 8 and execute step 6, 7, 8, 9 in sequence iteratively. Until almost no more new nodes can be found, abort the iteration and execute step 10.
10: Alias resolution for routing nodes. Perform alias resolution on all routing nodes. Merge different interface IPs belonging to the same node.
11: Extract Bi-fan structures and combine the ones with common nodes to obtain each PoP.
12: Obtain the city-level location of each PoP according to corresponding landmarks in L whose probed paths pass through the PoP and output the final PoP partition result R.

level location consistency of the same subnet (/24 and smaller ones) IPs, the similarity of the number of routing hops and single-hop delays of probed paths for IPs in the same city, a high completeness PoP partition algorithm for IP geolocation is proposed.

A. MAIN STEPS

The proposed algorithm and its main steps are as follows. The framework is shown in Fig. 4 and partial variables involved and their meanings are shown in Table 1. In the following steps, probed paths analysis (step 3, 4, 5), subnet IPs filtering and non-regional IPs exclusion (step 7, 8) as well as alias resolution for routing nodes (step 10) are pivotal and need to be described in detail. So the three parts are elaborated separately in the following three subsections and partial variables involved and their meanings are also shown in Table 1.

B. PROBED PATHS ANALYSIS

Probed paths analysis is one of the core parts of the algorithm. Through paths analysis the backbone routing nodes that do not belong to any PoP are excluded and the non-backbone nodes are obtained. According to the "low-high-low" distribution characteristic of single-hop delays between adjacent routers in the probed paths, the probed paths are analyzed and divided as follows:

1) For the IP set T of an area, $\forall IP_i, IP_j \in T$, divide their paths into $Path_{outside}$ and $Path_{inside}$ according to the statistical results.
2) Analyze the $Path_{inside}$ segment for each IP. Extract routing nodes and links of the specific area. Obtain the set of non-backbone routing nodes S and corresponding links of the specific area. The backbone routing nodes are excluded because they exist in the $Path_{outside}$ segment.
3) Analyze the $Path_{outside}$ segment for each IP. On the basis of their number of routing hops u_i, u_j and the minimum value of each single-hop delay v_{ix}, $v_{jx}(1 \leq x \leq u)$, construct HDV: $V_i\,(u_i, v_{i1}, v_{i2}, \cdots, v_{ix}, \cdots, v_{iu})$, $V_j\left(u_j, v_{j1}, v_{j2}, \cdots, v_{jx}, \cdots, v_{ju}\right)$ for IP_i, IP_j.
4) Use the clustering algorithm to divide IPs with similar vectors (in other words, IPs that belong to the same city in the area) into the same subset and these subsets are: $T_1, T_2, \ldots, T_m, \ldots, T_n$.
5) The Euclidean distances of HDVs for IPs in the same subset and between different subsets are calculated by the formula (1), and the threshold is set according to the distance values for judging whether two IPs belong to the same subset.

$$D_{ij} = \sqrt{\left(u_i - u_j\right)^2 + \sum_{x=1}^{u}\left(v_{ix} - v_{jx}\right)^2} \tag{1}$$

6) $\forall T_m$, count the mean value of routing hops $u\bar{_{T_m}}$ and each single-hop delay $v_{T_{mx}}$, construct the reference HDV: $V_{T_m}\left(\bar{u}_{T_m}, v_{T_{m1}}, v_{T_{m2}}, \cdots, v_{T_{mx}}, \cdots, v_{T_{m\bar{u}}}\right)$.

The regional routing nodes and links are obtained according to the above method. At the same time, the reference HDV of each city in the area can be constructed and used for the subnet IPs filtering in the next section.

Probe IPs of Zhengzhou in Henan, China with a vantage point deployed in Beijing, China. Table 2 shows an example of routing hops and single-hop delays in 10 times of probed results for IP "222.137.96.1". As can be seen from Table 2, from the sixth to the tenth hop, each delay value is significantly higher and each represents a backbone routing node. However, from the first to the fifth and the eleventh to the fifteenth hop, each delay value is relatively low and one represents a routing node in Beijing and another in Zhengzhou, respectively. Therefore, for the IP "222.137.96.1" in Zhengzhou, the eleventh to the fifteenth hop represents the $Path_{inside}$ segment and we can extract five routing nodes in Zhengzhou from it; the first to the tenth hop represents the $Path_{outside}$ segment. Take the minimum value of each single-hop delay in the segments and we can construct the $HDV$for this IP like: (10.0, 10.1, 12.4, 12.2, 10.4, 13.3, 40.3, 42.1, 56.1, 51.3, 48.0). Similarly, according to the above method, using the HDV of each IP, the reference HDV for

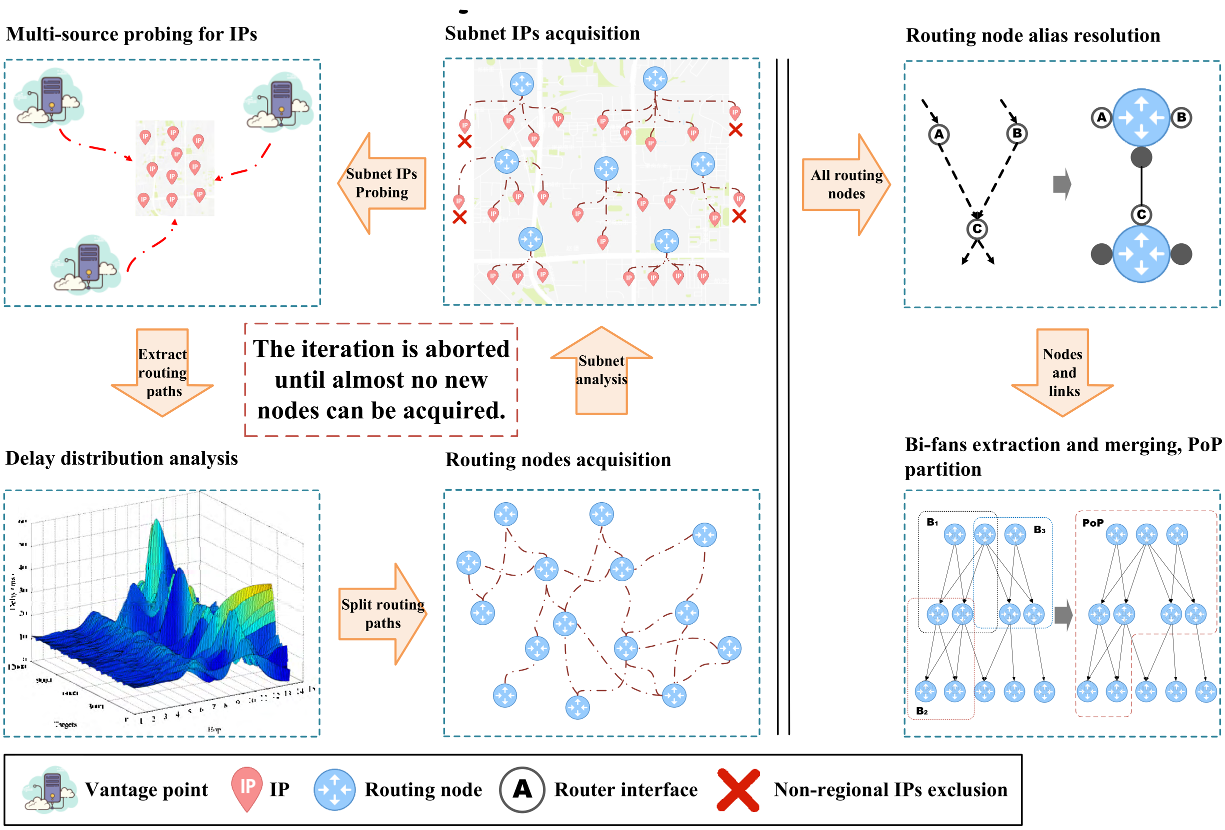

FIGURE 4. Framework of the proposed algorithm.

TABLE 1. Explanation of partial variables involved in the following subsections.

Variable	Explanation
T	An IP set to be probed
L	A landmark set used to determine the locations of PoPs obtained.
$Path_i$	The probed path for IP_i in T_n
$Path_{outside}$	The routing path segment outside an area, that is from the source IP to the last hop routing node before entering the area (*i.e.*, the first two segments of the "low-high-low" three-segment routing path)
$Path_{inside}$	The routing path segment inside an area, that is from the first hop routing node to the last one in the city where the destination IP is located (*i.e.*, the last one segment of the "low-high-low" three-segment routing path)
HDV_i	The Hops-Delay Vector for IP_i
S	A set of routing nodes obtained from $Path_{inside}$ analysis in a specific area
S_{subnet}	A set of subnet IPs of all routing nodes in the set S
S'_{subnet}	Exclude IPs in S_{subnet} that do not belong to a specific area and generate S'_{subnet}
R	The final PoP partition result

Zhengzhou can be constructed like: (10.0, 9.50, 10.4, 9.20, 10.1, 12.2, 38.6, 35.7, 49.9, 45.3, 44.5). And it can be used for filtering subnet IPs in Zhengzhou.

C. SUBNET IPS FILTERING AND NON-REGIONAL IPS EXCLUSION

Subnet IPs filtering and non-regional IPs exclusion is another core part of the algorithm. Based on the similarity of the number of routing hops and single-hop delays in probed paths between IPs of the same city, the subnet IPs are further filtered as follows:

1) After performing subnet analysis on all IPs in the set of routing nodes S in the area, other IPs belonging to the same subnet are obtained and the set S_{subnet} is constructed. $\forall IP_k \in S_{subnet}$, probe it and construct *HDV*: V_{IP_k}.
2) Calculate the Euclidean distance between V_{IP_k} and any reference *HDV* V_{T_m}. Determine whether IP_k belongs to the subset T_m based on the distance value, that is, whether it belongs to the specific area:
   a. If $\exists V_{T_m}$, make $D_{kT_m} \leq D_{threshold}$, that is to say, V_{IP_k} is most similar to the *HDV*s of the nodes in the subset T_m. Then we think that IP_k should belong to T_m and belong to the specific area;
   b. If $\forall V_{T_m}$, make $D_{kT_m} > D_{threshold}$, that is, V_{IP_k} is not similar to the *HDV* of any IP in the area. So we believe that IP_k should not belong to the specific area and exclude it.
3) After excluding all subnet IPs that are not in the area, construct the new set S'_{subnet}.

TABLE 2. An example of probed results for "222.137.96.1".

The serial number of each probed result	The single-hop delay of each hop (*ms*)														
	1	2	3	4	5	**6**	**7**	**8**	**9**	**10**	11	12	13	14	15
1	13.4	12.4	15.4	14.0	19.0	**41.5**	**49.3**	**67.1**	**51.3**	**56.6**	16.4	13.5	21.0	1.6.	14.1
2	11.7	14.9	14.4	19.9	13.3	**43.4**	**55.4**	**59.8**	**54.1**	**50.3**	17.9	23.5	14.2	2.0.	11.7
3	12.2	14.7	12.2	10.4	16.4	**40.3**	**57.6**	**56.4**	**53.7**	**51.0**	18.8	11.0	11.5	3.3.	12.7
4	13.5	14.4	15.0	10.7	18.5	**42.6**	**42.4**	**61.6**	**58.9**	**52.2**	18.0	33.8	12.2	1.6.	10.9
5	13.8	15.4	15.6	17.4	19.0	**44.5**	**57.5**	**64.9**	**57.1**	**48.0**	27.3	10.9	12.9	21.1	12.9
6	11.4	13.5	18.1	11.3	21.3	**49.8**	**52.5**	**57.7**	**53.4**	**49.4**	39.2	12.7	23.1	1.1.	14.0
7	11.8	14.1	15.1	18.8	18.0	**50.4**	**52.6**	**60.4**	**57.4**	**57.5**	29.0	13.5	20.9	10.8	12.0
8	12.5	12.8	14.4	20.2	16.3	**47.9**	**42.1**	**56.1**	**63.2**	**48.8**	19.2	20.9	22.9	13.4	20.6
9	11.7	14.9	17.5	14.9	15.8	**55.2**	**68.5**	**68.7**	**63.0**	**52.7**	18.8	22.5	21.6	14.2	13.7
10	10.1	14.1	17.4	17.2	17.6	**44.6**	**47.7**	**56.5**	**60.7**	**55.8**	28.8	20.7	13.5	17.0	23.9

Subnet IPs of the routing nodes in the area can be filtered to exclude the boundary ones that do not belong to the area according to the above method. The probed results of the remaining subnet IPs can be used to obtain new routing nodes of the area. For example, for Zhengzhou, set its reference *HDV*to: (10.0, 9.50, 10.4, 9.20, 10.1, 12.2, 38.6, 35.7, 49.9, 45.3, 44.5), and the *HDV*of a subnet IP is: (8.00, 6.90, 12.4, 19.2, 27.1, 55.6, 48.6, 45.7, 39.9, 16.0, 20.6). By calculation, the Euclidean distance value of the two vectors is about 74.6, which is significantly larger than the threshold (20 in this paper). This shows that the subnet IP does not belong to Zhengzhou. Then we calculate the distances between the *HDV*of the IP and the reference *HDV*s of other cities. The results show that all the distance values are greater than 20. So the subnet IP need to be excluded.

D. ALIAS RESOLUTION FOR ROUTING NODES

In order to further ensure the completeness of the PoPs in an area, multiple alias resolution algorithms are performed on the routing nodes obtained to avoid the bigger PoP being divided into smaller ones. Taking Zhengzhou, China as an example, Fig. 5 shows the process of alias resolution, nodes merging, and PoPs partition. As shown in Fig. 5(a), the alias analysis is not performed. The Bi-fan structures are extracted and merged according to the links between the routing nodes and three small-scale PoPs (*i.e.*, PoP_1, PoP_2, and PoP_3) are obtained. After the alias analysis, it is found that in the three PoPs, the nodes R_2 and R_6, R_4 and R_{11}, R_5 and R_8, R_9 and R_{12} belong to the same router respectively, and PoP_1, PoP_2, and PoP_3 belong to the same PoP. So we merge them and the *PoP* showed in Fig. 5(b) is the final result.

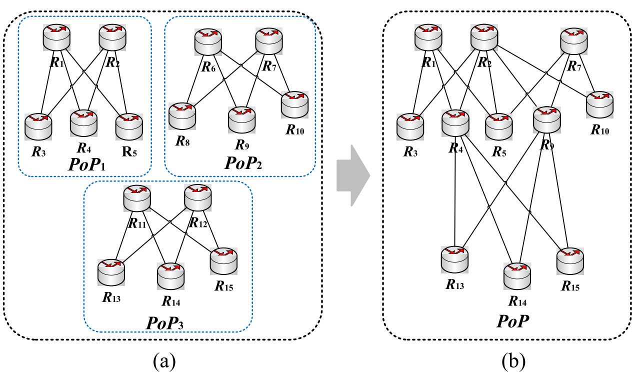

FIGURE 5. Alias resolution, nodes merging, and PoP partition.

IV. PRINCIPLES ANALYSIS ABOUT THE PROPOSED ALGORITHM

Keys to the above algorithm to achieve relatively complete PoP partition result in a specific area are: 1) subnet (/24 and smaller scale) IPs' city-level locations are often consistent; 2) when any two IPs of the same city in an area are probed by the same source, the number of routing hops of the probed path segments that from the source IP to the last routing node before entering the city where the destination IP is located are often the same and their corresponding single-hop delays tend to have similarities; 3) it is reasonable to perform subnet IPs filtering based on similarity of Hops-Delay Vectors (*HDV*s). So the principles of the algorithm is analyzed from three aspects: city-level locations consistency of subnet IPs; similarity of routing hop count and single-hop delay in probed results of IPs in the same city; the rationality of subnet IPs filtering based on vector similarity.

A. ANALYSIS OF CITY-LEVEL LOCATION CONSISTENCY OF SUBNET IPS

The IP address is composed of the net-id and the host-id. The two parts combining together can uniquely identify a host on the Internet. Only hosts with the same net-id can communicate directly. Hosts with different net-ids can only communicate through the gateway. But such divisions are not very flexible in some cases. To enhance network flexibility, the network is allowed to be divided into smaller ones, which are called subnets. When an ISP performs IP address allocation, for the convenience of management and maintenance, a contiguous IP address segment is often assigned to users in the same area. For example, a C class IP segment (each IP in the segment is composed of a 3-byte net-id and a 1-byte

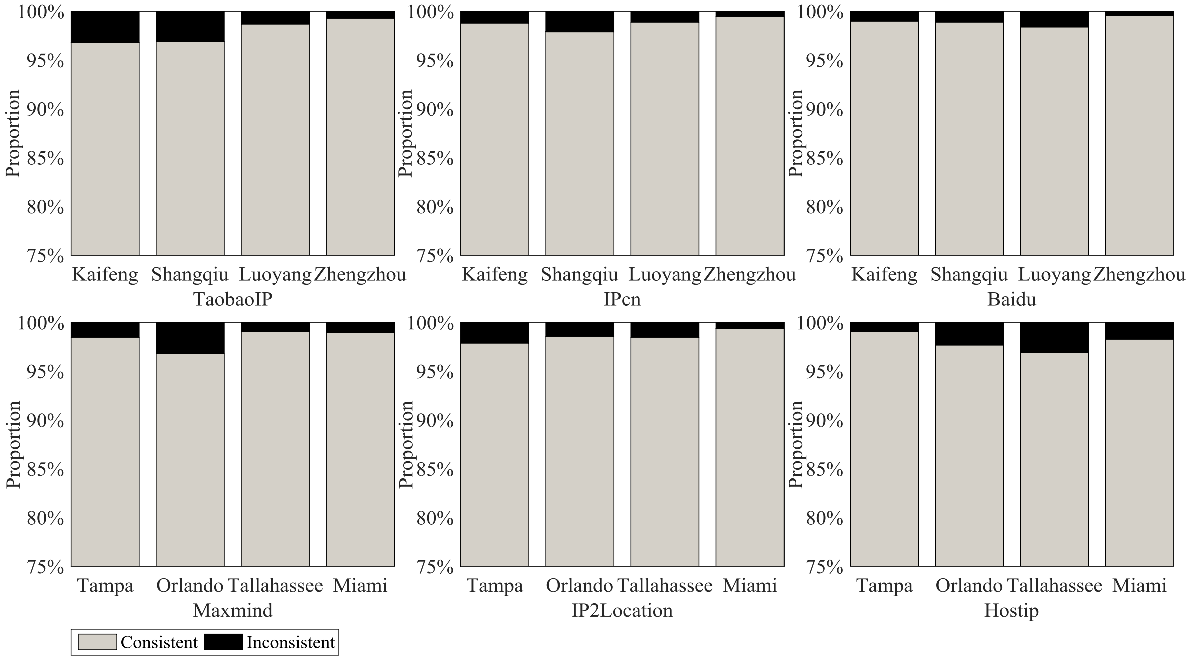

FIGURE 6. Statistics on the consistency of city-level location of the subnet IP.

host-id and belongs to a /24 block) is usually assigned to the same city [21]. Tozal *et al.* [22] counted 21,089 subnets in six ISPs, such as "PCCW Global", "nLayer", "France Telecom", "Telecom Italia Sparkle", "Interroute", "MZIMA" and found that more than 99.8% of the subnets are /24 or even small. The /24 block can be further divided into smaller subnets according to specific needs within a city. Therefore, locations of IPs within the same subnet (/24 and smaller scale) are often very similar and almost all in the same city [21], [23].

As we can see in Fig. 6, for eight cities of Kaifeng, Shangqiu, *etc*. in Henan, China, and Tampa, Orlando, *etc*. in Florida, US, each takes 50,000 IPs obtained through subnet analysis. After querying multiple geolocation databases such as TaobaoIP and Maxmind, *etc*., it is found that the ratio of subnet IPs of each city whose city-level location are consistent with the initial analysis IPs' is almost over 95%.

Based on the consistency of subnet IPs' city-level locations, perform subnet analysis on regional routing nodes to obtain other IPs in the same subnet and use them as target IPs to be probed. It can reduce the dependence on geolocation databases and the impact of incorrect database location information. At the same time, it can increase the number of target IPs, which can result in richer and more reliable routing nodes and links. Thus in this way, a relatively complete PoP partition result of the area is possible to obtain.

B. SIMILARITIES ANALYSIS OF ROUTING HOPS AND CORRESPONDING SINGLE-HOP DELAYS

Routers connected to the Internet often have the characteristic of serving a specific area according to their geographical distribution. ISPs often place a large number of routers in the same PoP to serve a specific area [3]. The statistical analysis shows that when the same vantage point is used to probe IPs of the same city in an area, the number of routing hops of the routing path segments that from the source IP to the last routing node before entering the city where the destination IP is located is almost the same. And their corresponding single-hop delays tend to have similarities and always fall into a certain range. However, probed results for IPs belonging to different areas often do not have such similarities.

Using the vantage point deployed in Beijing, China, 10,000 IPs in Luoyang and Zhengzhou, China are probed respectively. Similarly, using the vantage point deployed in New York City, US, 10,000 IPs in Tallahassee and Miami, Florida are probed respectively. Fig. 7(a), 7(b), 7(c), and 7(d) show the statistics of hop count and single-hop delays in the probed paths of the four cities. Through comparative analysis, it can be seen that single-hop delays of the probed paths exhibit a distinct "low-high-low" three-segment distribution characteristic; for probed results of IPs in the same city obtained by the same source, the number of routing hops is similar and the single-hop delay corresponding to each hop also approaches a certain range. But the results of IPs in different cities are different. This statistical feature can be used to filter the target IPs in an area and exclude IPs that are not within the area.

C. RATIONALITY ANALYSIS OF SUBNET IPS FILTERING BASED ON VECTOR SIMILARITY

After analyzing IPs obtained through subnet analysis, it is found that the geographic locations of a small number of

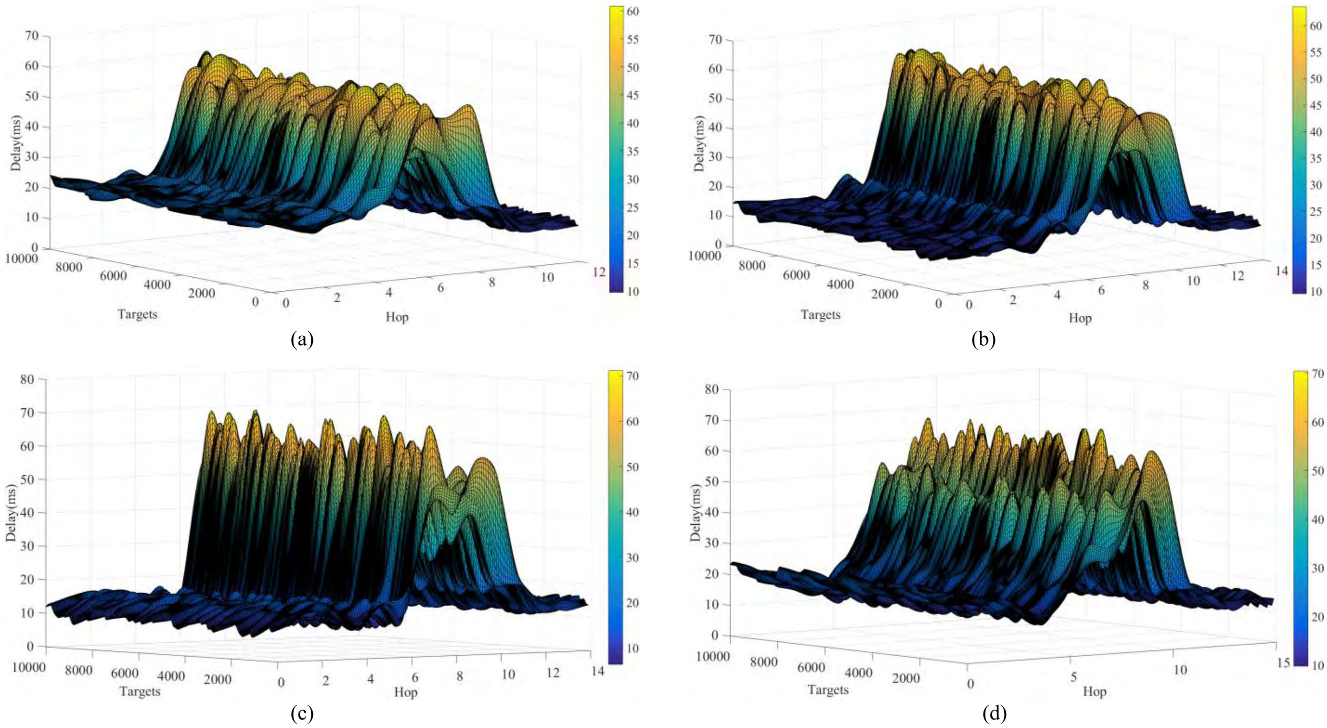

FIGURE 7. Statistics of hops and single-hop delays.

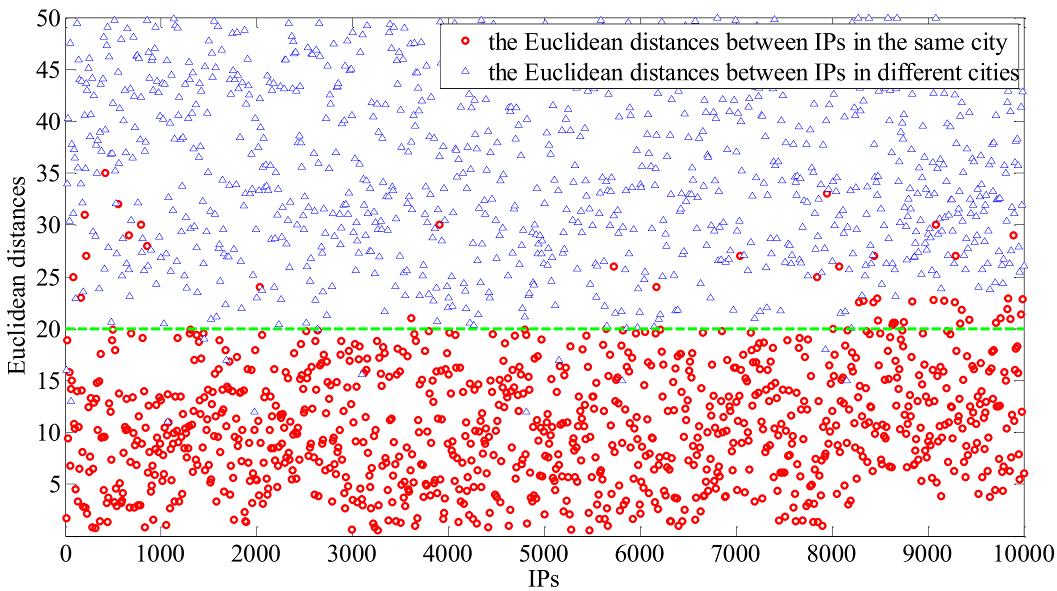

FIGURE 8. Comparison of the *HDV* Euclidean distances between IPs in the same city and in different cities.

IPs may be inconsistent with the location of initial IPs and do not belong to the same area. This is because the part of IPs may belong to the regional boundary area, and the logical topological positions have a certain gap with their real geographical positions. These subnet IPs that do not belong to the area should be excluded to ensure the reliability of IPs to be proved extended by subnet analysis.

For probed results of IPs inside an area, path segments outside the area are analyzed. It is found that IPs with strong similarity in routing hops and single-hop delays often belong to the same city in the area. For probed results of IPs in different cities, differences in routing hops and single-hop delays are obvious. Even if the number of routing hops is the same, there is a certain difference in the single-hop delay. For subnet IPs inside the area and the ones do not belong to the area, probed results also have the above differences. These differences can be used to filter subnet IPs and exclude the non-regional ones. Therefore, according to probed results, the proposed algorithm clusters IPs in a specific area into different IP subsets (*i.e.*, IP sets of different cities in the area) and calculates the *HDV* Euclidean distances of IPs in a subset and between subsets. Set a threshold according to distance calculation results and construct a reference *HDV*of each subset at the same time. Then calculate the Euclidean distance between the *HDV*of the subnet IP and each reference *HDV*. According to the distance value, subnet IPs can be filtered and non-regional ones can be excluded. In this way, the reliability of target IPs to be probed extended by subnet analysis can be ensured and the number of routing nodes and links acquired in the area can be greatly improved.

Using probed results of 10,000 pairs of subnet IPs in Zhengzhou, China respectively, construct the *HDV*s and calculate the Euclidean distance between each other to obtain 10,000 distance values. In addition, using probed results of 10,000 subnet IPs in Zhengzhou, China, 10,000 ones in Xi'an, Shaanxi Province, construct the *HDV*for each IP and the Euclidean distance between the 10,000 pairs of *HDV*s are calculated. 10,000 distance values are also obtained. Fig. 8 shows the distribution of the two types of distance values. It can be seen from the figure that the Euclidean distances between the *HDV*s of IPs belonging to the same city in the area are small, almost all less than 20, while the Euclidean distances between *HDV*s of IPs from different areas are large, almost all greater than 20. So subnet IPs filtering based on vector similarity is reasonable to some extent.

V. EXPERIMENTAL RESULTS

In order to verify the effectiveness of the proposed algorithm, Henan, China and Florida, US are selected as specific areas. PoP partition experiments of these two areas are carried out by using the algorithm of this paper. The parameter settings are described in Subsection *A*. The completeness of the PoP partition result in each area will be analyzed in Subsection *B*. In Subsection *C*, PoP partition results in the above specific areas respectively obtained by PoP-Geo, PoP-NTA and the proposed algorithm are compared and analyzed. As mentioned above, a PoP is usually attributed to a certain city in an area. When probing IPs in a city, paths often pass through the PoP of the city. This feature can be used to perform city-level geolocation of IPs in a specific area. Therefore, in order to further test the effect of the proposed algorithm, city-level geolocation tests of target IPs in the two area are performed and results are analyzed in Subsection *D*.

A. PARAMETER SETTINGS

By comparing multiple geolocation databases, IPs with consistent city-level location information are obtained as targets to be probed in a specific area. Among them, query "TaobaoIP", "IPcn" as well as "Baidu" and get IPs of the same location results of the three databases. Select ones in Henan, China that belonging to the ISP named "China Unicom". 4,396,399 IPs are obtained as the targets. Similarly, query "Maxmind", "IP2Location" as well as "Hostip" and get IPs of the same location results of the three databases. Select ones in Florida that belonging to the ISP named "AT&T". 1,383,986 IPs are obtained as the targets of the area.

Vantage points are deployed in Beijing, Shanghai, Chengdu, and New York, Chicago, and Houston to probe IPs in Henan and Florida from three different regions, respectively. When probing, in order to reduce the situation that destination IPs do not respond to a single type of packet and improve IPs probe rate, respectively send three protocol packets such as ICMP, UDP, and TCP, *etc*. to target IPs; based on the consideration of the working period of routers and terminal devices, 100 times of probing are performed on IPs during the day and night in the experiments.

In [22], a subnet inference algorithm based on active probe was proposed. Given a target IP, the algorithm can infer the largest-scale subnet to which the target IP belongs and IPs of the same subnet with the target IP. The algorithm first sets a /31 temporary subnet containing the target IP and then initiates active probe for each IP in the temporary subnet. According to the response type to the probing packet, it is determined whether IPs in the temporary subnet belong to the same subnet in the actual network. The temporary subnet is expanded by one level if all IPs belong to the same subnet. Probing and discrimination are continued. Until an IP does not belong to the same subnet with other IPs, the corre-

TABLE 3. Parameter settings for PoP partition experiments in two areas.

Specific area	Geolocation database	Number of IPs to be probed	ISP	Location of the vantage point	Times of probing	Type of probing packet	Alias resolution algorithm
Henan (CN)	TaobaoIP IPcn Baidu	4,396,399	China Unicom	Beijing Shanghai Chengdu	100	ICMP UDP TCP ICMP-paris UDP-paris	Mercator Ally RadarGun
Florida (US)	Maxmind IP2Location Hostip	1,383,986	AT&T	New York Chicago Houston			

sponding temporary subnet is reduced by one level and the reduced subnet is used as the largest subnet to which the target IP belongs. The subnet inference accuracy of the algorithm is relatively high, reaching more than 93%. In view of the accuracy, in the experiment, the algorithm proposed in [22] will be used to perform subnet analysis on the regional routing nodes. And on the basis of this classic method, we further improved it. The subnet IPs obtained through this method are further filtered and non-regional subnet IPs are excluded.

In order to ensure the accuracy of alias resolution and improve the completeness of PoP partition results, the three algorithms of Mercator [11], Ally [24] and RadarGun [25] are used in this experiment to perform alias resolution on routing nodes in an area. Specific parameter settings are shown in Table 3. Based on the above settings, the PoP partition experiments are carried out for Henan and Florida respectively.

B. POP PARTITION RESULTS

The completeness of the PoP partition results will be analyzed in two aspects to illustrate the effectiveness of the proposed algorithm.

1) COMPLETENESS ANALYSIS FROM THE NUMBER OF NODES INCLUDED IN EACH POP

During the execution of the algorithm, the improved subnet analysis of routing nodes is iterated several times until almost no new routing node is available through probed paths analysis. Using routing nodes and links obtained in each iteration to perform PoP partition. For the partition results corresponding to different iteration times, the number of routing nodes included in each PoP is statistically compared and analyzed.

Performing statistical analysis on the PoP partition results corresponding to different times of iteration and then determine the city-level location of each PoP. Take PoPs in Kaifeng, Shangqiu, Luoyang, Zhengzhou in Henan, China, and in Tampa, Orlando, Tallahassee, and Miami in Florida, US as examples. For different times of iteration of the proposed algorithm, compare the changes in the number of nodes included in the respective PoPs of the eight cities. Table 4 and Fig. 9 show the increase of routing nodes included in PoPs.

It can be seen from Table 4 and Fig. 9 that as the number of iterations increases, the total number of nodes included in each PoP obtained in Henan and Florida increases fast. However, when a certain number of iterations is reached, the number of nodes grows steadily and the size of each PoP hardly changes. In Table 4, the background color of the data changes from green through yellow to red. In this process, the size of each PoP is gradually increasing and the rate is getting slower and slower. This is because in the initial stage of the algorithm, a certain number of initial IPs being probed are unreachable and the number of routing nodes acquired in the area is small. Along with the iteration of the improved subnet analysis, many new paths are obtained through the probing of subnet IPs and the number of routing nodes as well as links are greatly increased. So the size of each PoP is also greatly increased. However, in the later stage of the algorithm, new routing information acquired in the area becomes less

TABLE 4. Increase of nodes in PoPs of eight cities.

Times of iteration	Number of nodes included in each PoP							
	Henan (CN)				Florida (US)			
	Kaifeng	Shangqiu	Luoyang	Zhengzhou	Tampa	Orlando	Tallahassee	Miami
1	725	810	998	1154	861	985	1287	1345
2	945	1180	1256	1686	1125	1286	1615	1876
3	1179	1475	1660	2095	1487	1502	1895	2224
4	1326	1689	1828	2406	1691	1721	2092	2501
5	1411	1775	1956	2616	1805	1879	2243	2621
6	1503	1861	2065	2801	1912	1966	2331	2716
7	1586	1945	2183	2995	1994	2035	2387	2774
8	1653	2025	2276	3138	2165	2110	2435	2795
9	1704	2073	2344	3228	2204	2152	2466	2819
10	1741	2111	2397	3304	2237	2195	2482	2834
11	1777	2141	2443	3367	2249	2221	2499	2848
12	1782	2156	2476	3406	2258	2234	2511	2855
13	1796	2163	2489	3425	2264	2239	2517	2857
14	1801	2167	2501	3437	2267	2241	2519	2861
15	1803	2169	2505	3446	2268	2242	2521	2861

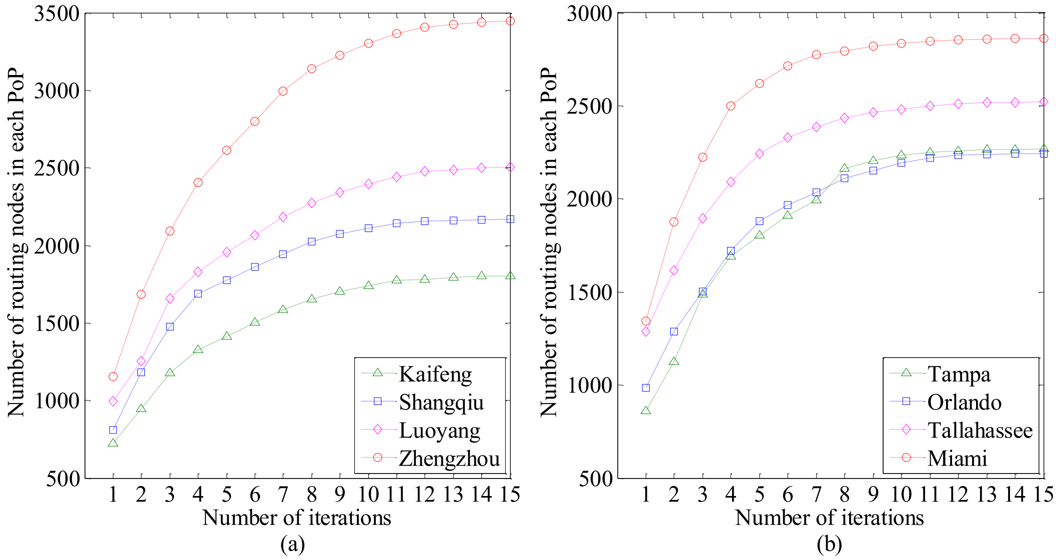

FIGURE 9. As the number of iterations increases, increase of nodes included in pops of different cities.

and less. The growth rate of the number of nodes of each PoP is gradually slowing down. It can be seen that each PoP finally obtained by the proposed algorithm has a large scale and includes a large number of routing nodes. As the number of iterations increases, a relatively complete PoP partition result of a specific area can be obtained by the proposed algorithm.

TABLE 5. Comparison of PoP partition results before and after alias resolution.

Specific area	Number of cities in the area	Whether alias resolution has been performed	Number of PoPs obtained	Number of routing nodes included in each PoP						
Henan (CN)	18	No	32	$PoP_1 \sim PoP_{32}$						
				1126	695	1476	1744	662	2431	1405
				1245	1217	827	1355	2089	1256	1170
				3255	1179	1152	445	189	105	81
				76	114	125	132	154	86	102
				69	168	91	59			
		Yes	18	$PoP_1 \sim PoP_{18}$						
				1034	676	1521	1803	643	2505	1491
				1202	1326	810	1411	2236	1209	1153
				3446	1144	1190	433			
Florida (US)	66	No	121	$PoP_1 \sim PoP_{121}$						
				1011	2116	2021	1699	2109	2488	1435
				1526	1229	1368	201	253	835	1988
				321	215	378	1025	1751	456	587
				1411	1377	899	1025	1166	998	589
				1106	925	1053	1441	1250	1306	1417
				477	383	285	786	684	871	669
				435	512	483	363	…	196	225
		Yes	66	$PoP_1 \sim PoP_{66}$						
				1421	2242	2268	1439	2521	2861	1568
				1402	1488	1408	875	963	1016	2068
				589	664	885	1155	1987	753	672
				223	445	551	684	…	577	664

2) COMPLETENESS ANALYSIS FROM THE NUMBER OF POPS OBTAINED IN EACH AREA

Using routing nodes obtained after the 15th iteration of the proposed algorithm and two times of partition are performed before and after the alias resolution of these node. Table 5 shows the PoP partition results of the two areas. As shown in the table, for Henan, China, a total of 32 PoPs are obtained when no alias resolution is performed. But after alias resolution, it is found that PoP_1 and PoP_{19}, PoP_3 and PoP_{20}, PoP_4 and PoP_{21} and PoP_{22}, PoP_6 and PoP_{23} and PoP_{24}, PoP_7 and PoP_{25}, PoP_9 and PoP_{26}, PoP_{11} and PoP_{27}, PoP_{12} and PoP_{28} and PoP_{29}, PoP_{15} and PoP_{30} and PoP_{31}, PoP_{17} and PoP_{32} belong to the same PoP and each located in the same city. Combine them one by one and the actual number of PoPs is 18. These 18 PoPs are located in 18 cities in Henan. Similarly, for Florida, a total of 121 PoPs are obtained when no alias resolution is performed. But after alias resolution, it is found that PoP_1 and PoP_{67}, PoP_2 and PoP_{68}, PoP_3 and PoP_{69}, PoP_5 and PoP_{70}, PoP_6 and $PoP_{71} \cdots$ belong to the same PoP. After merging the actual number is 66 (the number is too large and the partition results are not all listed). These 66 PoPs are located in 66 cities in Florida. The use of alias resolution avoids bigger PoPs being divided into multiple smaller ones and a more complete partition result can be got.

Some PoPs seem to get smaller in size and the number of nodes included in them decreases through alias resolution. This is because IPs of the interfaces belonging to the same router in the PoP are correspondingly merged. PoPs obtained after alias resolution are more complete although the number of nodes seems to be reduced. And the partition result can reflect the true network structural characteristics.

C. COMPARISON WITH TWO TYPICAL ALGORITHMS

Using the same topology measurement data obtained according to the parameter settings before, PoP partition results in Henan, China and Florida, US obtained by PoP-Geo, PoP-NTA and the proposed algorithm are compared and analyzed in this section. Results of the three algorithms of some cities in the two areas are shown in Table 6 and Table 7. It can be seen that the proposed algorithm has the best effect (although the efficiency is not very high). It is mainly reflected in the following aspects:

- PoPs obtained by the proposed algorithm contain the largest number of routing nodes and are relatively complete. Whether in Henan or Florida, PoPs of this algorithm are the largest in terms of the scale. And scales of these PoPs are about 5.2 times of ones obtained by PoP-Geo, 4.2 times of ones obtained by PoP-NTA. The average is about 3.3 times and 3.5 times respectively.
- The number of PoPs obtained by the proposed algorithm is equivalent to the number of cities in each area. Many smaller PoPs that should belonging to the larger ones in the same city are merged through alias resolution. Each PoP is more complete.

D. TESTS FOR IPS CITY-LEVEL GEOLOCATION

As mentioned above, a PoP is usually attributed to a certain city in an area. when probing IPs in a city, paths often pass through the PoP of the city. The location of the target IP can be determined by the location of the PoP which target IP's probed paths passing through. So PoPS can be applied to city-level IP geolocation. The higher the completeness of PoPS, the lower the failure rate of IP geolocation. Therefore, in order to further test the effect of the proposed algorithm, city-level IP geolocation tests are performed and results are analyzed in this section.

1) TEST 1

For Henan and Florida, 250,000 IPs from each area with known positions are selected and used as targets to be

TABLE 6. Comparison of the results of three algorithms for Henan.

Specific area	Number of cities in the area	Algorithm	Number of PoPs obtained	Number of routing nodes included in PoPs in four cities				Duration (*h*)
				Kaifeng	Shangqiu	Luoyang	Zhengzhou	
Henan (CN)	18	PoP-Geo [14]	41	349	787	542	1305	36.5
		PoP-NTA [15]	35	434	611	802	1022	51.6
		Proposed	**18**	**1803**	**2169**	**2505**	**3446**	**66.1**

TABLE 7. Comparison of the results of three algorithms for Florida.

Specific area	Number of cities in the area	Algorithm	Number of PoPs obtained	Number of routing nodes included in PoPs in four cities				Duration (*h*)
				Tampa	Orlando	Tallahassee	Miami	
Florida (US)	66	PoP-Geo [14]	217	1053	941	895	1510	48.3
		PoP-NTA [15]	154	736	899	1014	1211	60.1
		Proposed	**66**	**2268**	**2242**	**2521**	**2861**	**74.7**

TABLE 8. Comparison of the geolocation results using PoPs obtained by different iterations.

Number of iterations	Specific areas / The total number of target IPs											
	Henan (CN) / 250000						Florida (US) / 250000					
	Failed to geolocate		Location cannot be given		Geolocation result is incorrect		Failed to geolocate		Location cannot be given		Geolocation result is incorrect	
1	37,252	14.9%	25,750	10.3%	11,502	4.6%	46,155	18.5%	31,693	12.7%	14,462	5.8%
5	19,505	7.8%	11,043	6.4%	8,462	1.4%	25,250	10.1%	20,500	8.2%	4,750	1.9%
10	9,756	3.9%	8,253	3.3%	1,503	0.6%	13,011	5.2%	12,250	4.9%	750	0.3%
15	**2,253**	**0.9%**	**1,755**	**0.7%**	**498**	**0.2%**	**2,749**	**1.1%**	**2,481**	**1.0%**	**268**	**0.1%**

TABLE 9. Comparison of the geolocation results using PoPs obtained by different algorithms.

Algorithms	Specific areas / The total number of target IPs											
	Henan (CN) / 250000						Florida (US) / 250000					
	Failed to geolocate		Location cannot be given		Geolocation result is incorrect		Failed to geolocate		Location cannot be given		Geolocation result is incorrect	
PoP-Geo [14]	35,511	14.2%	24,448	9.8%	11,063	4.4%	29,483	11.8%	16,213	6.5%	13,270	5.3%
PoP-NTA [15]	31,465	12.6%	21,233	8.5%	10,232	4.1%	41,731	16.7%	23,717	9.5%	18,014	7.2%
CRLB [26]	10,235	4.1%	6,701	2.7%	3,534	1.4%	7,244	2.9%	4,252	1.7%	2,992	1.2%
Proposed	**1,491**	**0.6%**	**1,258**	**0.5%**	**233**	**0.1%**	**2,014**	**0.8%**	**1,449**	**0.6%**	**565**	**0.2%**

geolocated. PoP partition results obtained by different iterations of the improved subnet analysis method are selected respectively for the geolocation tests of these IPs.

Table 8 gives a comparison of geolocation results for target IPs using PoPs obtained by different iterations. When the location information of a target IP cannot be given by the PoPs obtained (data with blue background in the table), or the geolocation result is incorrect and inconsistent with the known location of the IP (data with orange background), these situations are collectively considered to be failed to geolocate (data with purple background).

It can be seen from the data with purple background that as the number of iterations increases, the total number and proportion of IPs that failed to geolocate continues to decrease. And the data with blue background is also significantly decreased which means the number and proportion of IPs that the location information cannot be given by PoPs are decreased. This is because as the number of iterations of the improved subnet analysis increases, the number of routing nodes obtained in a specific area is continuously increased. Then the number of nodes included in PoPs obtained is continuously increased and the scale of each PoP is continuously expanded. The probability of target IPs probed paths passing through PoPs is greatly increased. As a result, the probability of successful geolocation for target IPs is greatly increased.

2) TEST 2

In order to further test the effect of alias analysis on improving the completeness of PoP partition results, the final results in Henan and Florida obtained by PoP-Geo, PoP-NTA and the proposed algorithm are used to geolocate another 250,000 IPs with known positions from each area. At the same time, a typical geolocation algorithm named "CRLB" [26] is also used to geolocate these target IPs. The experimental results are shown in Table 9.

It can be seen from Table 9 that the data with blue and orange background are also decreased and this means in comparison when using PoPs obtained by the proposed algorithm to perform target IPs geolocation, the effect is the best. This is because PoP-Geo and PoP-NTA have not performed alias resolution on routing nodes before obtaining PoPs. Routing nodes that should belong to the same PoP in the area are divided into multiple smaller PoPs. However, there are no landmarks whose probed paths passing through some of these small-scale PoPs and their city-level locations are unable to determine. So they cannot provide location information for target IPs and cannot be used for city-level geolocation. Locations of other small-scale PoPs may be incorrect due to a small number of inaccurate landmarks. These PoPs are also unable to geolocate IPs correctly. CRLB can obtain relatively good results, but it will also be affected when the number of landmarks is limited. However, the proposed algorithm performs alias resolution on all routing nodes before PoPs partition. Multiple small-scale PoPs that belong to the same PoP are merged together. Usually there are some landmarks whose probed paths passing through these PoPs and by which can determine the city-level locations of these PoPs. Even if there may be a small number of landmarks with incorrect location information, the locations of the large-scale PoPs are obtained by the voting mechanism and this can avoid the impact of these errors. So the larger PoPs can successfully geolocate target IPs.

The above experimental results verify that a complete PoP partition in a specific area can be obtained by the proposed algorithm. And these PoPs can still be used for accurate city-level geolocation of target IPs even if the number of landmarks is limited or the landmarks are inaccurate.

VI. CONCLUSION

Complete PoPs can geolocate target IPs with high success rate. However, PoPs obtained by some existing methods may be difficult to meet the geolocation requirements. In this paper a high completeness PoP partition algorithm for IP geolocation is proposed. A variety of experiments such as PoP partition and target IPs geolocation in different areas of China and US are designed to verify the proposed algorithm. Experimental results show that compared with several classic algorithms like PoP-Geo, PoP-NTA and CRLB, PoPs obtained by the proposed algorithm have a great improvement in completeness and with these PoPs the success rate of IP geolocation can be greatly improved even if the landmarks are insufficient or inaccuracy. Although the algorithm achieves better PoP partition and IP geolocation results, it still has the problem that when dealing with a large number of routing nodes, the efficiency is not high enough. Our future research work will focus on the issue mentioned above.

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