An AS Border Judgment Method based on IP Path Information

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***Abstract*—Mapping router-level topology to AS-level topology can help us understand Internet structure intensively. Judging AS border is an important mapping technology in the issue. However, the open problem has not been studied carefully yet. We proposed a general AS border model based on IP path information and the concept of AS border sequence. Three judging rules (the exclusion rule, intersection rule and demarcation rule) are proposed and demonstrated based on the concept. Therefore, an AS border judgment method named JBR (Judging Border by Rules) is designed. By analyzing Chinese AS borders from IP path information measured by CAIDA's *skitter* tool, we find the JBR is better than the method named JBA (Judging Border by Alias) which based on alias resolution on both discovering border addresses and confirming their administrative domains. Experiments also imply that the two methods are complementary to each other.**

Keywords- IP network; IP path; AS border

I. INTRODUCTION

Internet topology is usually classified to two types: router-level topology and AS-level topology. Building the mapping relationship between two level topologies enables us to understand Internet structure intensively and is helpful to Internet control and management. For example, by the mapping relationship we could obtain AS-level connectivity information at a finer granularity which can provide physical level insight into AS peering relationships [1].

Building the mapping relationship between two level topologies need to solve two different problems that look like same, that is, "Which AS does an IP address belong to?" and "Which AS does a router represented by this IP address belong to?" The first problem is described as IP-to-AS mapping problem, and Mao [2, 3] conducted an intensive study on this problem and proposed an accurate systematic mapping algorithm. However, the second problem is lack of further research yet. This paper thus focuses on the problem.

The difference between two problems is that sometimes those addresses belong to one router unnecessarily belong to the same AS. Generally, the router and its interfaces belong to the same AS in the interior of an ISP network, but the border router and its interfaces may belong to two adjacent ASes respectively.

This phenomenon is due to the two addresses of a link usually with the same prefix, which makes two addresses of the border link both belong to one AS, although two border routers belong to two adjacent ASes respectively. Fig.1 (a) shows this situation. The sequence $p_1p_2p_3p_4$ on an IP path represents left interface addresses of 4 sequential routers, p_1 and p_2 belong to AS A while p_3 and p_4 belong to AS B, but router R_2 belong to AS B.

Two problems are also close related. The judgment accuracy of the second problem relies on the accuracy of IP-to-AS mapping directly. Unfortunately, we still could not solve the second problem completely even if there is complete accurate IP-to-AS mapping. The center of the second problem is to distinguish the borders of ISP networks, that is, discover border routers and judge which AS they belong to.

It is hard to identify AS borders by direct measurements, but easy to obtain IP path information measured by *traceroute* tool. Based on some AS border characteristics observed in path information, we propose a novel judging method named as JBR (Judging Border by Rules) which discover border routers and judge their administrative domain by restricted relationships among addresses of IP paths.

II. RELATED WORK

IP-to-AS mapping reveals the relationship between an IP address and an AS number and it is the key technology of building the mapping relationship between two level topologies. Usually, an IP-to-AS mapping table can be constructed from BGP routing tables by inspecting the last AS (the origin AS) in the AS path for each prefix. Mao proposed several methods to improve the mapping accuracy [2, 3].

To judge whether a router is a borer router, usually we should aggregate those addresses (so-called router alias) belonging to the same router. This process is called alias resolution. The standard technology for alias resolution was introduced by Pansiot and Grad [4]. It detects aliases by sending *traceroute*-like probes (to a high-numbered UDP port) directly to the potentially aliased IP address. If the probed router send the "UDP port unreachable" response with the address of outgoing interface as the source address which is different from that of incoming interface, then the address of outgoing interface and that of incoming interface must belong to the same router.

If these interfaces of a router belong to multiple ASes, then the router is a border router. The advantage of this method is that the condition of judgment is exact and there are no error judgments if we suppose the IP-to-AS mapping is accurate. The method is limited by two factors: (1) the current alias resolution technique is limited by measurement right so that the addresses can be aggregated are not so much; (2) having

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interfaces belong to multiple ASes is the sufficient condition but not the necessary condition for judging border routers. For example, Fig.1 (a) shows that R_1 is a border router of AS A and its interfaces all belong to A.

For mapping a discovered border router to the AS it belong to, [4] applied a simple judgment, that is, mapping each border router by picking the AS that is most frequently assigned to its interfaces. Chang argued that if an border router's interfaces were mapped to $\{AS_1, \ldots, AS_N\}$ then the router must belong to $\{AS_1, \text{peer}(AS_1)\} \cap \ldots \cap \{AS_N, \text{peer}(AS_N)\}$ [1], here peer(AS_i) denotes any of AS_i's peers. Therefore, two mapping rules were proposed: (1) Intersection rule: if the above intersection set reduces the candidate set to a single element set, the sole AS in the candidate set is then adopted as the administrative domain of the given router; (2) Majority rule: if given router is known to have more than four interfaces and more than two thirds of them are mapped to one AS, that AS is chosen as the router's administrative domain. Because of the richness of AS peering relationships, there are more AS candidates in the candidate set. So it is difficult to reduce the candidate set to a single element set by intersection. Only about 20% of the discovered border routers can be mapped to their administration domain successfully [1].

We uniformly call above methods as JBA (Judging Border by Alias) which based on the alias resolution technology. The method is insufficient on both discovering AS borders and judging their administrative domains.

III. IP Path and AS Border Information

A. Partition Characteristics of AS Border

Before analyzing the characteristics of AS border, we should define some notions and marks as follows:

Definition 1 [Path Information]

- IP path: $p = p_1 \ldots p_n$, namely an addresses sequence, here $n \geq 2$. If $p_i = p_j$ then $p_i = p_j = q$, q is an anonymous address representing a router which does not response *traceroute*'s probe. $P = \{p\}$ is the set of all paths; I(P)/I(p) is the set of addresses in P or p. Br(P)/Br(p) is the set of border addresses in P or p.
- L_R is the set of logical router identifier, including the unknown router identifier U_R; L_{AS} is the set of AS number, including the unknown AS number U_{AS}. L_{AS}' is the subset of L_{AS} which is not null.

Definition 2 [Mapping function]

- R: I $\rightarrow$ L_R is a function to map an IP address to a logical router identifier. The anonymous address is mapped to the unknown router identifier U_R.
- M_I: I $\rightarrow$ L_{AS} is a function to map an IP address to an AS number. The function is constructed by IP-to-AS mapping technique.
- M_R': $L_R|P \rightarrow L_{AS}$' is a function to map a logical router identifier to a set of AS number with path information. $M_R'(R(p_i)|p)$ is a set of AS number which $R(p_i)$ belong to on the path p.
- M_R: $L_R \rightarrow L_{AS}$ is a function to map a logical router identifier to an AS number. The anonymous router is mapped to the unknown AS identifier U_{AS}.

$M_R(R(p_i))$ is not necessarily equal to $M_I(p_i)$. With above definitions, the AS border judgment problem can be described as follows: Given P and M_I, to conclude Br(P) and confirm M_R(Br(P)).

In practice, one AS border router usually connects with the adjacent AS border router directly. So our analysis based on the following assumption: if a path $p = p_1 \ldots p_n$ traverse AS A and B, then there are p_i and $p_{i+1} \in \{p_1, \ldots, p_n\}$ to make $M_R(R(p_i))$=A and $M_R(R(p_{i+1}))$=B, that is, two adjacent AS border router's interfaces would appear on a IP path and be adjacent with each other directly.

Intuitively, if there is $M_I(p_i) \neq M_I(p_{i+1})$ on a path $p = p_1 \ldots p_i p_{i+1} \ldots p_n$, which means there is an AS border around the link $\langle p_i p_{i+1} \rangle$. Though the location of border link can not be confirmed, we hope confirm a candidate scope for the border link under some situations. Fig.1 discusses several border link distinctions with specific instances. Here the addresses sequence $p_1p_2p_3p_4$ exists on a forward path, R_i=R(p_i), $M_I(p_1)=M_I(p_2)$=A, $M_I(p_3)=M_I(p_4)$=B. Three sub-graphs show that link $\langle p_1p_2 \rangle$, $\langle p_2p_3 \rangle$ and $\langle p_3p_4 \rangle$ are all possible to be the border link. We should notice that an address on an IP path is the source address of the "ICMP time exceeded" message sent by a router to respond a *traceroute* probe. Ideally, the address corresponds to the incoming interface where the packet entered the router. However, RFC 792 does not explicitly state which address the router should use [5]. Practically, some routers assign the source address with the outgoing interface in the responding message [6]. Because routing is not necessarily symmetric, the interface receiving the *traceroute* probe and the interface sending the ICMP message may be different.

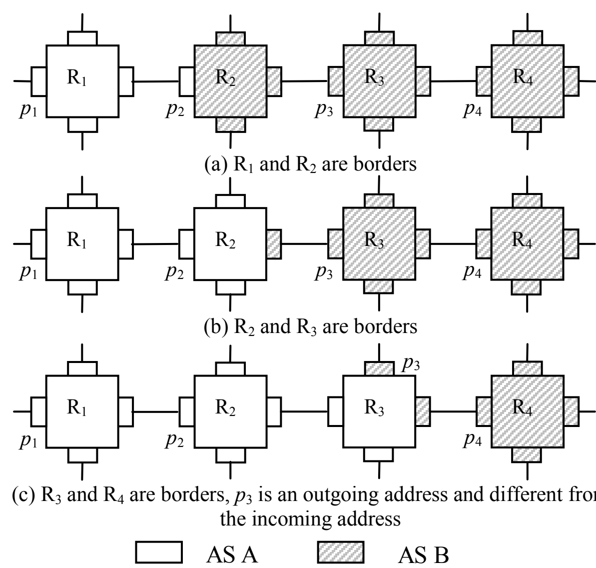

Figure 1 Different border is possible with same addresses sequence

In Fig.1(a), p_1~p_4 are left interface addresses, $M_I(p_2)$=A, but $M_R(R_1)$=A, $M_R(R_2)$=B; in Fig.1(b), p_1~p_4 are left interface addresses, $M_R(R_2)$=A, $M_R(R_3)$=B; in Fig.1(c), p_1, p_2 and p_4 are left interface addresses while p_3 is outgoing interface and different from the left incoming address, $M_I(p_3)$=B, but $M_R(R_3)$=A, $M_R(R_4)$=B.

Several details should be mentioned: (1) there may be other different distinctions under special circumstances with the above addresses sequence, but usually the three distinctions include most situations under our assumption; (2) we do not choose the candidate border from following sequence: $p_ip_{i+1}p_{i+2}$, $M_I(p_i)$=A , $M_I(p_{i+1})$=B, $M_I(p_{i+2})$=C, the sequence involves two or three borders, and it is not suitable to get conclusion; (3) both AS A and B in Fig.1 do not represent IXP(Internet eXchange Points). An IXP provides interconnection service for multiple ISP through a shared infrastructure. Although an IXP may hold AS number and its addresses will appear on a forward path that traverses the IXP, usually it does not mean an AS border between the IXP and the previous ISP or next ISP on the path but means a border between the two ISP which interconnected in the interior of the IXP. Therefore if AS A (or B) on the above addresses sequence is an IXP, we do not choose the candidate border from the addresses sequence because it does not follow above partition characteristics.

Based on above analysis, the concept of border sequence is defined as follows:

Definition 3 [Border Sequence]

- For path $p = p_1 \ldots p_ip_{i+1}p_{i+2}p_{i+3} \ldots p_n$, if $M_I(p_i) = M_I(p_{i+1})$ = A, $M_I(p_{i+2}) = M_I(p_{i+3})$ = B, $p_i \sim p_{i+3} \neq$ q, then $s_I=(p_ip_{i+1}p_{i+2}p_{i+3})_{AB}$ is named as border sequence.
- Exclude $\langle p_ip_{i+1}\rangle$ as the border link between A and B, and confirm p_{i+2} as border address
- $S=\{s\}$ is the border sequence set; $I(S)/I(s)$ is the set of addresses in S or s; $B_r(S)/B_r(s)$ is the set of border addresses in S or s.

Let $s = (p_ip_{i+1}p_{i+2}p_{i+3})_{AB}$, which lies in a path p. For each logical router represented by relative address on the s, there are 4 mapping properties as follows:

1) $M_R'(R(p_{i+1})|s) = \{A,B\}$;

2) $M_R'(R(p_{i+2})|s) = \{A,B\}$;

3) if there exists $p_{i-1} \in I(p)$, $M_I(p_{i-1}) \neq A$, then $M_R'(R(p_i)|s) = \{M_I(p_{i-1}), A\}$, else $M_R'(R(p_i)|s) = \{A\}$;

4) if there exists $p_{i+4} \in I(p)$, $M_I(p_{i+4}) \neq B$, then $M_R'(R(p_{i+3})|s) = \{B, M_I(p_{i+4})\}$, else $M_R'(R(p_{i+3})|s) = \{B\}$.

The property (1) and (2) are obvious. The property (3) indicates that for the address p_i in the s, if there exists its left adjacent address p_{i-1} which does not belong to A on the original path p, then router $R(p_i)$'s mapping AS set is $\{M_I(p_{i-1}), A\}$, else the set is $\{A\}$; the property (4) is same as (3).

For the property (3), if exists the p_i's left address p_{i-1} which belong to B, that is $M_I(p_{i-1})$=B, then we consider the border sequence is invalid, because this indicates there is an AS level routing loop B-A-B on the original path p. We discard the sequence because it does not imply the border between A and B efficiently. The abnormal situation is due to the inaccuracy of IP-to-AS mapping and Mao discussed several reasons for the routing loop. There is also same abnormal situation in the property (4).

B. The Rules for Judging Borders

Based on the border sequence, AS border judgment problem can be described again as follows: Given P and M_I, construct S to conclude $B_r(S)$ and confirm $M_R(B_r(S))$.

A border sequence contains 3 potential border links. Under a given condition, we could exclude one link from the potential borders. The exclusion rule reveals the basic law of judging AS border.

[Exclusion rule]

For each border sequence $s = (p_ip_{i+1}p_{i+2}p_{i+3})_{AB}$, if there is a path $p = a_1 \ldots a_ja_{j+1} \ldots a_m \in P$, $p_i=a_j$, $p_{i+1}=a_{j+1}$, and exists $k \geq 2$ such that $M_I(a_{j+2}) = \ldots = M_I(a_{j+1+k})$=A, then $\langle p_ip_{i+1}\rangle$ is not the border link and $p_{i+2} \in B_r(s)$, $M_R'(R(p_{i+1})|s) = \{A\}$.

Proof: We prove by contradiction. Suppose that $\langle p_ip_{i+1}\rangle$ is the border link between A and B, then $R(p_i)$ must belong to A and $R(p_{i+1})$ belong to B. Consider two different cases: (1) if $M_R(R(a_{j+2}))$=A, then there is an AS level routing loop A-B-A, similarly if $M_R(R(a_{j+3}))$=A, there is also an routing loop, contradiction; (2) if $M_R(R(a_{j+2})) \neq A$ and $M_R(R(a_{j+3})) \neq A$, since $M_I(a_{j+2}) = M_I(a_{j+3})$=A, then the router $R(a_{j+2})$ and $R(a_{j+3})$ are both borders (belong to B or C), and a_{j+2}/a_{j+3} is the outgoing address of responding message from $R(a_{j+2})/R(a_{j+3})$. It is infrequent to discover consecutive border addresses that belong to A after the border link $\langle p_ip_{i+1}\rangle$ between A and B, so we can exclude $\langle p_ip_{i+1}\rangle$ as the border link. Then whatever $\langle p_{i+1}p_{i+2}\rangle$ or $\langle p_{i+2}p_{i+3}\rangle$ is the border link, $R(p_{i+2})$ must be a border router. At the same time, $M_R'(R(p_{i+1})|s)$ must be mapped to A.

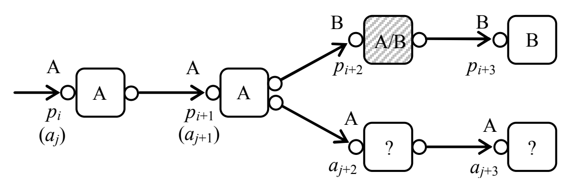

Figure 2 Exclude $\langle p_ip_{i+1}\rangle$ as the border link between A and B, and confirm p_{i+2} as border address

The rule shows, if the link $\langle p_ip_{i+1}\rangle$ on the border sequence s also exists on another path p, and there are consecutive addresses belong to A after the link on the path p, then we can exclude link $\langle p_ip_{i+1}\rangle$ from the potential border links and confirm p_{i+2} as a border address. Fig.2 shows the situation.

With the border sequence's mapping properties and the exclusion rule, we can assign AS mapping set $M_R'(R(p_i)|s)$ for each router $R(p_i)$ on the S. However, router $R(p_i)$ may be mapped to different candidate set $M_R'(R(p_i)|s)$ on different sequence s. We use $C_R(p_i|S)$ to represent the family of different candidate set which $R(p_i)$ is mapped, that is $C_R(p_i|S) = \{M_R'(R(p_i)|s) \mid p_i \in I(s), s \in S\}$. The intersection rule shows how to deduce border address's administrator domain from the family.

[Intersection rule]

If there is the generalized intersection $C_R(p_i|S)=\{X\}$, $X\in L_{AS}-\{U_{AS}\}$, then $M_R(R(p_i)) = X$.

For each p_i in a border sequence s, $M_R'(R(p_i|s))$ represents $R(p_i)$'s possible AS mapping set, while $C_R(p_i|S)$ represents the family of the AS mapping sets under different sequence s. If the generalized intersection of $C_R(p_i|S)$ contains a single element, the sole AS is the administrative domain of $R(p_i)$. For each p_i in the specific sequence s, the candidate ASes in the set $M_R'(R(p_i|s))$ do not excess two due to the properties of the border sequence. Therefore, this rule is more efficient on deriving a single AS through intersection than Chang's method.

If a border address's administrator domain can be determined by applying the intersection rule, we can use the demarcation rule to confirm more border addresses.

[Demarcation rule]

For each $s=(p_i p_{i+1} p_{i+2} p_{i+3})_{AB}$ on which the exclusion rule can be applied, if $M_R(p_{i+2})=B$, then $p_{i+1}\in B_r(S)$.

The rule shows, if the address p_{i+2} has been confirmed as border address and $R(p_{i+2})$ belong to B, then p_{j+1} will be confirmed as border address. Fig.3 shows the situation.

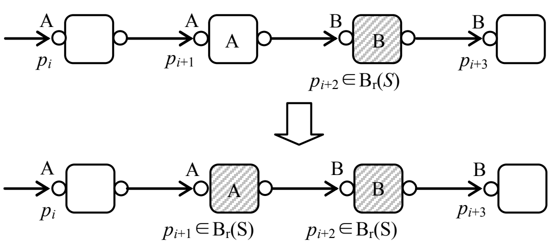

Figure 3 If $R(p_{i+2})$ is a border router and mapped to {B}, then confirm $R(p_{i+1})$ as border router

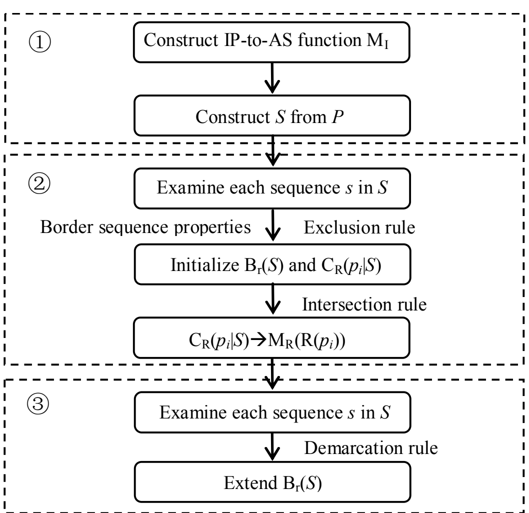

Figure 4 AS border judging steps

Thus we obtain above judging rules which could be considered universal: the exclusion rules are demonstrated and the intersection and demarcation rule are summary and conclusions about path information.

The judging method consists of three steps (as shown in Fig. 4):

1) Pretreatment. Construct the IP-to-AS mapping function M_I from BGP tables and the border sequence set S from the path set P;

2) The primary confirm of the border address set $B_r(S)$ and M_R function. Examine each s in S, for a router $R(p_i)$ which address p_i appear in the s, initialize the $B_r(S)$ and the family of AS sets $C_R(p_i|S)$ by applying the exclusion rules and the border sequence properties. $M_R(R(p_i))$ is primarily confirmed by applying the intersection rule on $C_R(p_i|S)$;

3) The further confirm of the border address set $B_r(S)$. Based on the above results, examining each s again, the border address set $B_r(S)$ are further confirmed and extended by applying the demarcation rule.

IV. Experiments and Analysis

Applying above method, we analyze the AS borders of China mainland. In the paper, we use the IP path data measured by *skitter*. *Skitter* is a tool deployed around Asia, Europe and North America by CAIDA to collect Internet IP path data from 1998 [7]. In the experiments, we focus on the *skitter* data collected from 05/10/2007 to 05/15/2007 which contain all paths measured by 17 monitors aimed to about 970,000 destinations. We abstract the IP paths within the China mainland to build the path set P which contains 1,327,358 paths and 28,827 addresses.

IP-to-AS mapping is build by analyzing BGP routing tables. We use 66 BGP router's route data collected from 05/10/2007 to 05/15/2007 by RouteViews [8]. There are 75 Chinese ASes in the path set P. By searching Whois information, it is known that 72 ASes belong to ISP and 3 ASes belong to IXP (that is AS 4847, 4840 and 4789).

A. *Comparison of the Different Methods*

We use both JBA and JBR to judge Chinese AS borders and compare their judgment results. Two methods are applied on the same path set P.

JBA firstly aggregate those addresses belong to the same router from the address set $I(P)$. We use an alias resolution tool named *iffinder* developed by CAIDA to measure all addresses in set P, and find 4,089 alias pairs among which there are 1,365 addresses different from the addresses in set P. The 2,871 routers are aggregated based on these aliases, among which there are 71 border routers can be discovered. JBA finds totally 187 border addresses (belong to 71 border routers respectively) among which there are 32 addresses does not appear in set P, then the total number of border addresses discovered by JBA in set P is 155.

JBR abstracts the border sequence set S from P firstly, there are 10,502 valid sequences out of the totally 10,665 border sequences, which indicates potential AS borders of 113 AS pairs. Although JBR only selects AS border addresses from the sequence set *S*, the exclusion rule uses all IP path information in the set *P*. The parameter *k* in the exclusion rule is assigned as 2. Tab.1 compares the results of different methods.

Tab.1 shows that JBR can discover more border addresses than JBA. The common addresses discovered by both two methods are little. There are two reasons for this phenomenon: (1) the technology of two methods is different essentially; (2) the border sequence definition limits the number of possible border addresses in set *S*. Experiments indicates that about 2/3 addresses discovered by JBA does not appear in the set *S*. So the two methods are complementary to each other.

Among the 155 addresses discovered by JBA, applying Chang's method, only 9% addresses can be successfully confirmed which administrative domains they belong to. The ratio of JBR successfully confirming the border's administrative domain is higher than that of JBA. Chang did not discuss the judgment about border links, our method confirm 87 border links.

JBR introduces the concept of border sequence, which simplifies the complexity of AS border partition but also limits the number of possible addresses for judgment; meanwhile JBR introduces light error judgment because excluding several special situations. However, by building a series of judgment rules based on the clues derived from IP path information, JBR is better than JBA on both judging border addresses and confirming their administrative domains. Compared with JBA, JBR do not need measurement is another advantage. It takes about one hour for JBA to use *iffinder* to measure all addresses in set *P* while JBR deduces AS borders from IP path information in only 1~2 minutes.

TABLE I. COMPARISON OF DIFFERENT METHODS

Judging result	Comparison			
	Border address	*Confirmed on domain*	*Confirmed ratio*	*Border link*
JBA	155	14	9%	---
JBR	281	126	44%	87
JBA∩JBR	10	---	---	---

JBR does not use any alias resolution technology, so every address is considered as a logical independent router. This introduces a potential consistency problem, that is, whether there are multiple addresses belong to the same router practically, but JBR maps the logical routers which these addresses represent to different AS. Experiment result indicates that JBR is consistent on judging the administrative domain of those alias addresses.

B. Integrity Discussion

Compared with the number of border addresses, the number of border links (the border link judged by JBR is IP-level but not router-level) is more appropriate on discussing the integrity of the judgment results.

Although it is hard to calculate the border link's number in the path set *P* directly, we could estimate the number. By mapping each path *p* in set *P* to AS-level path with IP-to-AS technology, it is known that there are about 160 logical connections among the ISPs of China mainland. Supposing one AS logical connection corresponds average *m* router-level border connections and one border router connection corresponds average *n* IP-level border links which are not aggregated. Therefore, there are about $160*m*n$ border links in the path set *P*. Though the value of *m* and *n* are not confirmed, it is obvious that the number of border links discovered by our method is quite limited.

V. CONCLUSION

The paper proposes a novel AS border judgment method JBR based on IP path information. Our method defines the concept of border sequence and builds a series of judging rules by the relationships between addresses, which enable us to judge AS borders from IP path information. Our method, however, is limited by several factors: (1) the accuracy of IP-to-AS mapping technology; (2) the universality and validity of the IP path information; (3) the limitation of the border sequence's form and the light error judgment introduced by border sequences.

Experiments verify that JBR is better than JBA on both judging border addresses and confirming their administrative domains. Experiments also show us that two methods are complementary to each other, and we could get better judgment result if two methods are combined. Our method is inadequate on the integrity of the judgments, the AS border judgment is still an open problem.

ACKNOWLEDGMENT

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