Exploring the Spatial Granularity Trade-off in AS-Segment Tomography

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***Abstract*—Network tomgoraphy provides a scalable means of characterizing internal segment delay on the network with fewer measurements than router-level probing. However, its application to AS-level segment delay inference on the Internet is limited by a trade-off in flow aggregation granularity. This paper evaluates different aggregation granularities for AS-level segment measurements in network tomography using RIPE Atlas traceroute data. By comparing the tomography performance at three different measurement aggregation granularities, from coase to fine, we reveal that intermediate ingress/egress country-pair aggregation granularity offers the best trade-off between segment delay consistency and tomography estimation accuracy, enabling more accurate and scalable characterization of AS-segment delay distributions.**

***Index Terms*—Network Tomography, Measurement**

I. Introduction

Various efforts have been undertaken to characterize delay conditions on the Internet with the aim of improving Internet availability [1], [2], [3]. In particular, AS-segment delays have been investigated, as exemplified by CAIDA's work on identifying congestion at AS boundaries [4], [5], [6]. Measurement platforms have also been developed for this purpose. CAIDA operates the Ark measurement platform [7], while RIPE NCC monitors Internet conditions through RIPE Atlas [8]. They employ traceroute measurement in between worldwide vantage points for delay condition understanding.

Although measuring all routers along paths to multiple destinations contributes to accurate characterization of delay conditions, it also imposes scalability constraints and additional traffic burden on the network. Furthermore, traceroute-based measurements face observability limitations because intermediate routers do not always respond for security reasons, leaving many portions of the network unobservable [9]. Therefore, a more scalable method is required to characterize delay conditions with fewer measurements while preserving comparable observability.

Network tomography is a promising approach to addressing these challenges, as it infers the characteristics of individual path segments from end-to-end path measurements by exploiting spatial correlations among paths [10], [11]. Uilizing the inference, it can substantially reduce the number of measurements required while still enabling delay performance inference of unobserved intermediate segments. This property is particularly valuable for Internet-scale segment-level delay characterization, where intermediate administrative domains do not necessarily have incentives to cooperate with active measurements.

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For network tomography to be usable in practical applications (e.g. BGP traffic engineering), the inferred segments should be represented at AS-level granularity. At the same time, for tomography to be applicable, each segment must have consistent delay value. However, AS-level segment delays can be highly heterogeneous because traffic may traverse different internal routes and geographically distributed PoPs within the same AS. This delay consistency can be improved by refining the granularity of measurement aggregation within each AS segment. However, this refinement introduces a trade-off: finer granularity reduces the number of observations shared across paths and can therefore exacerbate the ill-posedness of the tomography problem, as illustrated in Fig. 1.

Considering this trade-off, we investigate an appropriate AS segment measurement aggregation granularity that simultaneously satisfies both estimation accuracy and within-segment consistency. We apply tomography to AS-level segment delay estimation using different measurement aggregation granularities for AS segments and compare estimation accuracy among them (Section IV). We find that partitioning multimodal ASes according to the pair of countries associated with the ingress and egress border routers satisfy trade-off between delay-distribution consistency and sufficient path sharing and data volume while preserving estimation accuracy.

II. Challenges in AS-level Tomography

Although using AS-level segments as tomography estimation units is desirable, applying tomography-based methods to AS-level segments introduces challenges. Network tomography aims to infer segment delays from end-to-end delay observations. In this formulation, the end-to-end delay vector y is modeled as $y = Rx$, where x is the segment-delay vector and R is the routing matrix. Each element of R indicates whether a given segment is traversed by each origin-destination (OD) flow [10]. This formulation assumes that, for OD paths sharing the same segment, the segment delay can be represented by a single consistent value, or at least approximated by a low-variance, unimodal distribution. However, this assumption

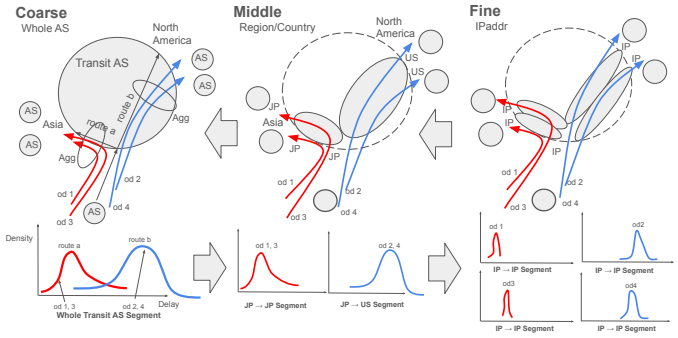


Fig. 1: Trade-off between the number of shared segments across paths and delay consistency within AS segments under three granularities

does not necessarily hold when whole-AS aggregation is used as the measurement aggregation granularity.

In particular, for geographically distributed ASes, delay cannot always be represented by a single low-variance unimodal value; instead, the delay distribution is often multimodal. This is because such ASes may contain diverse internal routes due to load balancing, as well as highly diverse routing dynamics with different hop lengths, ranging from short-distance routes to inter-regional paths, as illustrated in Fig. 1 (Coarse). For example, OD flows traversing shorter intra-AS routes and those traversing longer ones can form distinct modes in the delay distribution, reflecting differences in propagation distance within the AS. As a result, a single representative value for the whole AS is unlikely to capture its intrinsic delay characteristics, making whole-AS aggregation too coarse and violating the consistency assumption required for tomography.

One approach to applying tomography to AS-level segment delay estimation is to refine the measurement aggregation granularity. We define the granularity by grouping measurements passing through each AS according to the geographic region of its ingress and egress border router pairs (Fig. 1 (Middle)). Adopting a finer measurement aggregation granularity by treating segments as distinct instances according to adjacent ASes or ingress/egress routers could improve delay consistency within segments (Fig. 1 (Fine)). This motivates considering AS-segment granularity as a design parameter for tomography-based delay estimation.

A drawback of finer-grained aggregation is that it can reduce the number of OD flows sharing each AS segment, making the tomography problem less constrained. Because tomography exploits spatial correlations across paths, this reduction can exacerbate the ill-posedness of the inverse problem, leading to lower estimation accuracy. Fig. 1 illustrates this effect: as the aggregation granularity becomes finer, fewer OD flows share each AS segment. With whole-AS aggregation, one segment is shared by all four OD flows; with intermediate aggregation, two segments are each shared by two flows; and with the finest aggregation, no segment is shared across flows. Consequently, each unknown segment delay is constrained by fewer OD-flow observations, making segment-delay estimation less accurate.

Thus, the number of OD flows sharing each AS segment and within-segment delay consistency are in a trade-off relationship, and segment granularity is a parameter that controls this trade-off. At coarse granularity, sufficient path sharing is preserved for tomography estimation accuracy, but delay consistency within segments is often violated because of intra-AS diversity. At fine granularity, delay consistency improves, but path sharing decreases, making tomography more difficult and reducing estimation accuracy. Given this trade-off, this study aims to identify an appropriate AS-segment aggregation granularity that balances within-segment delay consistency and tomography estimation accuracy.

III. Data and Segment Granularities

Dataset: To explore an appropriate AS-segment aggregation granularity, we used one hour of traceroute data measured on the RIPE Atlas platform from 00:00 to 01:00 UTC on October 17, 2025. RIPE Atlas is suitable for this study because its globally distributed probes provide path measurements across diverse Internet locations. The traceroute data contain hop-level RTT measurements to routers along paths toward measurement destinations.

Since this study focuses on AS-segment delays rather than router-level delays, we converted hop IP addresses into AS numbers using CAIDA's Prefix-to-AS mapping dataset [12]. This conversion allows us to construct AS-level path representations from router-level traceroute measurements. To identify AS boundaries and ingress/egress border routers, we used bdrmapIT [13], which is designed to infer border-router addresses. Because Internet Exchange Point (IXP) IP addresses are generally not globally advertised through BGP and may therefore be missing from prefix-to-AS mappings, we additionally used CAIDA's IP-to-IXP-AS mapping data [14].

Granularities: Based on the AS-level paths, we constructed three aggregation granularities, as shown in Fig. 1. Our key idea is to refine AS-segment definitions using geographic information, by mapping ingress and egress border-router IP addresses to countries.

For IP-address-to-geolocation mapping, we used the RIPE IPmap dataset for October 17, 2025 [15]. Because RIPE IPmap does not cover all IP addresses, we supplemented missing geolocation mappings using the free IPinfo dataset [16].

In this study, we consider three granularities: (a) whole-AS aggregation, (b) ingress/egress country-pair aggregation, and (c) ingress/egress border-router IP-address-pair aggregation. Whole-AS aggregation treats all measurements traversing the same AS as a single segment. Ingress/egress country-pair aggregation groups measurements according to the countries of the ingress and egress border routers, allowing geographically different internal routes within the same AS to be separated. Ingress/egress border-router IP-address-pair aggregation distinguishes measurements by the specific IP addresses of the ingress and egress border routers, providing the finest granularity considered in this study.

IV. Estimation accuracy of Tomography

A. Experimental Setting

To investigate how the segment aggregation granularity affects tomography accuracy, we performed tomography with three segment granularities in Fig. 1. Here, tomography estimates the segment delay vector x from end-to-end path delays and a routing matrix constructed from the set of segments traversed by each OD flow by utlizing Ridge regression. The segments include both intra-AS segments and AS-boundary segments. For intra-AS segments, when an AS exhibited multimodal delay distributions, the AS was further subdivided according to the ingress/egress country pair along the path.

We evaluated the accuracy of the tomography results by comparing the estimated segment delays with the observed segment delays using the correlation coefficient and coefficient of determination R^2. In addition to segment-delay estimation accuracy, we examined to what extent the estimated delays under each segment granularity reproduced the observed AS-segment delay distribution by evaluating the reconstruction of the delay distribution of intra-AS segment delay. Because tomography requires consistency between end-to-end delay and the delay reconstructed from observed segment delays, we restricted the tomography estimation to OD flows whose reconstructed delay differed from the end-to-end delay by no more than ± 50 ms.

B. Results

The tomography results show that segment granularity affects both estimation accuracy and the reconstruction of observed AS-segment delay distributions. Table I summarizes the correlation coefficients and R^2 for each segment granularity. Fig. 2 shows scatter plots of estimated versus observed segment delays, and Fig. 3 compares corresponding delay distributions for AS 1299 as a representative example.

Among the three granularities, the ingress/egress country-pair granularity achieves the best balance between estimation accuracy and delay-distribution reconstruction. The correlation coefficient between the observed and estimated segment delays was 0.94, and R^2 from linear regression was 0.89, confirming high estimation accuracy (Fig. 2b). Furthermore, the reconstructed internal delay distribution for AS 1299 is also in good agreement with the observed distribution (Fig. 3b).

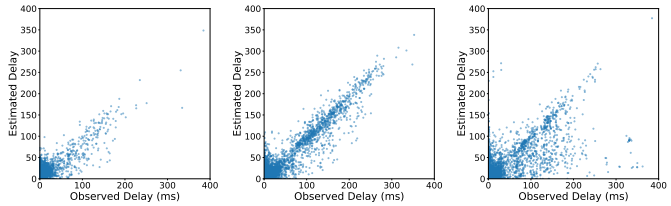
In contrast, the ingress/egress IP-address-pair granularity shows degraded estimation accuracy, with a correlation coefficient of 0.64 and an R^2 of 0.40 (Fig. 2c). This is likely because the number of path segments shared across OD flows decreases at this granularity, aggravating the ill-posedness of the problem. In fact, the estimated segment delays are often underestimated compared with the observed delays, suggesting the influence of L_2 regularization under weak segment identifiablity.

On the other hand, the whole-AS granularity achieves relatively high estimation accuracy but fails to reproduce the observed delay distribution, with a correlation coefficient of 0.84 and an R^2 of 0.70 (Fig. 2a). High estimation accuracy is likely due to the sufficient number of shared segments across OD flows, making segment-delay identification feasible. The limitation is evident in Fig. 3a, where the estimated delay distribution of AS 1299 collapses into a single representative value despite the multimodal observed distribution. This indicates that the delay characteristics of the AS segment are not adequately captured.

TABLE I: Segment delay estimation accuracy by granularity

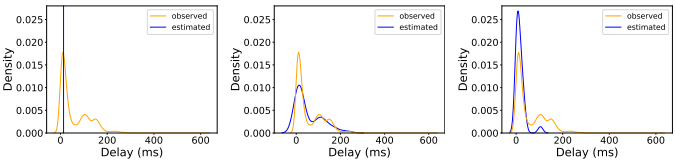
Metric	Whole-AS	Country	IPaddr
R^2	0.70	0.89	0.40
Corr. coef.	0.84	0.94	0.64

Overall, these results demonstrate a trade-off between preserving a sufficient number of shared segments across OD flows and maintaining low within-segment delay variance, suggesting that the ingress/egress country-pair granularity provides the most suitable balance.



(a) Whole-AS (b) Country (c) IPaddr

Fig. 2: Scatter plots of observed and estimated segment delays



(a) Whole-AS (b) Country (c) IPaddr

Fig. 3: Observed and estimated delay distributions for AS 1299

C. Limitations

This study is based on one hour of RIPE Atlas measurements, and the generalizability of the results over longer periods and different measurement settings remains to be evaluated. The results may also be affected by RIPE Atlas probe deployment bias and by the filtering of OD flows; future work should address these biases and unobserved delay components such as access-network delay and congestion.

V. Conclusion

In this work, we investigated the trade-off of the spatial measurement granularity in delay-based AS-level network tomography. We validated that AS-segment granularity defined by ingress/egress border-router country pairs is the most appropriate choice for the tomography estimation, as it appears to satisfy both the requirement for sufficient data volume and the reduction of within-segment delay variance. *This work does not raise any ethical concerns.*

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