ASRelVis: Exploring Autonomous System Relationships through 3D Lighthouse Layout with Linked Radial 2D Representations

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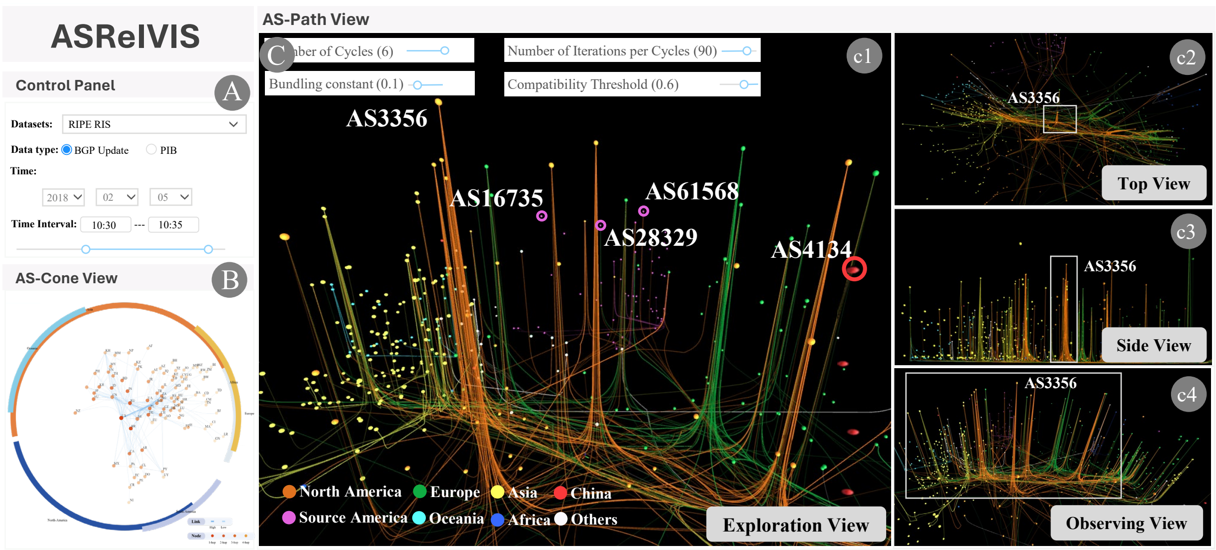

Figure 1: The interface of ASRelVis consists of three main views. (A) The Control Panel allows users to interactively select specific time periods of BGP routing data. (B) The AS-Cone View presents the aggregated routing capabilities and connectivity between countries to provide users with an overview and guide more detailed exploration of routing paths. (C) The AS-Path View presents complex BGP routing propagation paths, aiding users in exploring and analyzing routing behaviors at a granular level.

Abstract

Internet routing involves frequent interconnections between countries and regions. Analyzing network links and routing propagation is crucial for optimizing performance and making informed business decisions. However, existing visual analysis systems lack comprehensive multi-perspective analysis, hindering experts' ability to effectively analyze routing dynamics and activities. Few studies have explored the effective integration of 2D and 3D analysis techniques for routing data. We introduce ASRelVis, a novel system that combines 3D representations of AS routing relationships with 2D ASCone hierarchical views tailored to BGP route updates. These representations are seamlessly linked using interaction techniques, creating a perceptually uniform interactive space. Through collaboration with domain experts, we address challenges in data presentation and interaction. ASRelVis integrates 2D and 3D visualizations, guiding exploration based on 2D overviews. Case studies and expert interviews demonstrate its effectiveness and utility for analyzing BGP routing data.

Index Terms: Visual Analytics, Inter-domain Routing, Border Gateway Protocol, Information Visualization

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1 Introduction

Inter-domain routing analysis is a key concern of cyber security, thus it has been garnering widespread attention in studies conducted in fields such as routing path selection [4, 22], routing topology analysis [7, 21], routing leakage detection [41], and routing hijacking response [26, 38]. The inter-domain routing system with border gateway protocol (BGP) is a critical infrastructure in the Internet used to facilitate communication and data exchange between different Autonomous Systems (ASes). ASes are fundamental units of the Internet, each consisting of a set of network devices and routers managed and operated by a single administrative entity. The primary task of the inter-domain routing system is to determine the optimal path for data packets from a source AS to a destination AS, enabling data transmission across different autonomous systems [17].

Researchers typically analyze route propagation or specific ASes from multiple perspectives to uncover patterns in the selection of routing paths and the status of core routing nodes [35]. Research based on a 3D perspective provides an immersive representation of routing propagation through spatially arranged scatter plots, enhancing users' exploration of AS relationships and propagation paths. However, spatial hierarchical representations can obscure routing propagation across regions due to overlapping connections, hindering anomaly pattern detection, a recent research focus [32]. Conversely, research based on a 2D perspective facilitates rapid understanding of network topology and intuitive anomaly pattern identification but faces challenges in visually conceptualizing hierarchical routing structures and linking multiple perspectives in routing propagation analysis [37].

In this context, we present ASRelVis for visualizing and interacting with inter-domain routing capacity distribution and actual routing propagation paths. For a set of AS routing paths, given as lists of connected points, we create a 3D routing distribution and a region-aggregated radial 2D representation. AS-Cone view provide an overview of global routing relationships and regional routing capacities. AS-Path view reflect the propagation of routes among actual AS nodes. We link the views of these two representations implicitly through interaction and explicitly through a perceptually uniform coloring and highlighting. Figure. 1 shows the of inter-domain routing propagation, as depicted through the analysis of a BGP update dataset within our custom visualization framework. To demonstrate the usefulness of ASRelVis, we present two usage scenarios conducted by the domain experts on a real-BGP update dataset [30]. We further report the experts' feedback gathered from the post-study interviews. The main contributions of this paper are summarized as follows:

- ASRelVis, a novel visual analytics system that supports multi-perspective exploration of inter-domain routing propagation through the effective integration of both 2D and 3D visual representations. It provides a comprehensive and intuitive interface for interacting with Autonomous System connectivity and hierarchy, enhancing the understanding of internet routing dynamics for network analysts and researchers.
- A user study with cases and experts that demonstrates the effectiveness and usability of our system in analysis routing propagation. We also summarize the users' feedback on using the system to analyze BGP update data.

2 Related Works

2.1 Visualization for BGP Routing Analysis

The most common focus in visualizing BGP routing propagation is identifying and analyzing routing behaviors in routing update data [32]. Various statistical [1] and time series analysis [26] are being utilized for the detection of such routing incidents. Visual analysis techniques combined with geographical information present intermediate results and routing propagation paths, assisting users involved in the analysis process. Ulmer et al. [37] combine IP-Block and Geo-IP data to present the spatiotemporal distribution of routing nodes and propagation, which aids in the detection IP hijacks and misconfigurations. The primary data used for analysis are BGP updates and routing tables. To enhance analysis capabilities, some approaches incorporate additional traceroute data[39] and geographic data [10] as lookup information. Building on this foundation, ProBGP [38] introduces a progressive visual analytics application for global routing network monitoring. Visual analysis supports the detection of anomalous routing patterns and allows for a deeper understanding of prefix hijacks [36], routing leak [19], misconfiguration [25]and physical outages [20], especially while dealing with large BGP datasets.

Current visual approaches for BGP data analysis offer various forms of visual analytics mechanisms, including node-link diagrams [34], multi-view systems [41], timelines [6], and spatio-temporal representations [37]. Our work focuses on routing analysis by examining path propagation network evolution and the current state of BGP routing networks based on BGP updates. We utilize node-link representations of routing area distribution through node attribute-based graph embedding.

2.2 Visualization for Large-Scale Network Layout

Network data layout has been widely studied, various visualization techniques have been developed to analyze network topology and connectivity, such as graph embedding [12, 31] and force-directed edge bundling (FDEB) [14]. These systems can be roughly divided into two categories: visualizing routing network in 2D [5] and 3D [3].

Typically, 2D visualization techniques present the routing network from a top-down view, enabling analysts to investigate the dynamics of routing propagation on a large scale [9]. Commonly, various research employs node-link diagrams to layout network data, with methods such as force-directed layouts and community clustering proposed to reduce visual clutter caused by node overlaps [18, 42, 44]. NetSecRadar [45] utilizes a hierarchical force-directed graph layout to efficiently visualize multi-source cyber security event data, facilitating the identification and response to malicious network attack patterns. The t-FDP model [44] introduces a modified force-directed graph placement approach utilizing a bounded short-range force to accelerate the computation of the repulsive force, thereby enhancing neighborhood preservation in the layout. Furthermore, other research [46] aggregates community information based on context-aware sampling, aiding in understanding node importance, graph connections, and community stability in large-scale networks.

To mitigate the visual ambiguities resulting from a considerable volume of connections across, researchers have use aggregation methods, such as edge bundling [13] and density perception [28]. Edge-Path Bundling [40] leverages weighted shortest paths to cluster edges, reducing ambiguities compared to traditional bundling techniques. Additionally, line density approach [43] is employed to uncover latent trends by mitigating visual clutter resulting from overplotting. Image space coloring is utilized to represent data density and highlight similar regions in the plot. Although these 2D methods demonstrate effectiveness in analyzing network routing data, they cannot be directly adapted to the hierarchical nature of routing propagation. On the other hand, 2d-based methods can also be extended to 3D space. Several visualization systems have been proposed to support the analysis of large-scale routing network in 3D space. For example, 3D cluster-based FDEB algorithm [47] addresses the challenge of interactive analysis of 3D relational data. It combines geometrically close edges into bundles, reducing visual clutter and enhancing interpretability. VAST [29] visualizes the complex BGP routing topology from a 3D perspective. It leverages modified quad-tree and octo-tree algorithms to represent ASes, integrating peering relationships and anomalies to capture BGP routing behavior.

Recent studies increasingly utilize a combination of three-dimensional (3D) and two-dimensional (2D) representations to enhance the exploration of networks[15, 27]. Nature's reach [11] utilizes 3D rendering-based co-citation networks to visualize 150 years of data from the entire journal of *Nature*, revealing interdisciplinary trends in scientific research and providing new methods and perspectives. Additionally, graph embedding methods are crucial for enhancing node layouts and highlighting regional patterns. Attribute Graph Embedding [8] passing through a laplacian smoothing filter, effectively reducing high-frequency noise in node features. It also utilizes an adaptive encoder to iteratively enhance the filtered features for better node embeddings. GEGraph [33] employs an improved DeepWalk method [31] that introduces node attribute encoding to extend graph exploration and node layout techniques, effectively associating multiple neighboring node relationships. Inspired by GEGraph, we extend the node attribute-based DeepWalk method to 3D space, leveraging AS commercial relationships and regional associations to support the exploration of BGP routing propagation in a 3D context. In this work, we combine 2D and 3D representations to support BGP routing propagation analysis.

3 Background and Design Requirement

In this section, we introduce the background and data of BGP routing analysis, followed by the requirement analysis and system workflow.

3.1 Background

The Internet is indeed a complex network of autonomous systems (ASes) that are interconnected through the Border Gateway Protocol (BGP). As a critical infrastructure of the Internet, BGP plays a critical role in exchanging routing information between ASes and determining the optimal paths for data transmission across the global network. Understanding the dynamics of routing paths and the relationships between ASes is crucial for network analysts and researchers to ensure the security, stability, and efficiency of the Internet. Visualizing and analyzing the interplay between BGP routing changes, AS business relationships, and AS rankings can provide valuable insights into the complex dynamics of Internet routing. However, the intricate nature of route propagation relationships makes it challenging to effectively visualize and comprehend the multiple layers of intertwined information.

In this study, we adopt a hierarchical multi-perspective visualization approach in three-dimensional space, drawing on the insights from Barabási's seminal work in Nature [11], to depict the propagation of AS routes. To showcase the co-citation networks spanning 150 years of history, Nature's reach [11] employs a novel visualization method that portrays the epic of scientific history unfolding like the blooming of fireworks. This work spans 3D space, meticulously tracing the evolution from early seminal works to subsequent research advancements. The distinct colors employed therein serve to denote various disciplines. Notably, this visualization offers insights into the emergence of nascent fields stemming from the intersections of interdisciplinary research. In our work, ASes are metaphorically depicted as lighthouses within the network space, highlighting their crucial function in directing and forwarding Internet data to respective ASes. Additionally, by leveraging both 2D and 3D visual representations, it can provide network analysts with a comprehensive and intuitive understanding of the complex relationships and dynamics within the inter-domain routing system.

3.2 Data Description

BGP updates serve to propagate changes in routing relationships between Autonomous Systems (ASes), primarily involving announcements or withdrawals. The owner of an IP prefix announces network reachability information to neighboring ASes. Upon receiving these updates, neighboring ASes update their routing tables, appending their AS number to the AS path and propagate the information further. Conversely, route withdrawals prompt routers to notify neighboring ASes to update their routing tables. Each AS on the Interent learns about the next hop in the routing path for packets destined to specific IP addresses, thereby mantaining inter-domain routing stability.

The two common data sources for BGP data are the RIPE NCC Routing Information Service (RIS) [1] and University of Oregon RouteViews Project RouteViews [2] RIS has deployed 26 collection points worldwide, dumping BGP update data every 5 minutes and Routing Information Base (RIB) data every 8 hours. RouteViews has deployed 46 collection points, dumping update data every 15 minutes and RIB data every 2 hours. There are approximately 100,000 BGP route updates every 5 minutes, and millions of routing paths are dumped every 8 hours. For example, on April 3, 2024, from 0:00 to 8:00, RRC0 collected RIB data amounting to 405 MB uncompressed, containing 54,762,907 routing paths. From this data we mainly analyze the "*as_path*", "*from_asn*" and "*to_asn*". Since BGP updates only include AS numbers in the path, additional data is necessary to provide more information about ASes. Another dataset ASRank [3] maintained by CAIDA, records metadata for nearly 60,000 ASes. It includes information on ASes' associated organizations, locations, and also defines AS node rankings and a tier metric called the customer cone within the network [24]. We utilize RIS data from RIPE NCC to obtain routing updates and paths, while ASRank is used to apply the customer cone metric for categorizing all ASes into different tiers. Additionally, we combined 2D and 3D visualization techniques to analyze BGP routing propagation.

[1]Routing Information Service: https://www.ripe.net/analyse/internet-measurements/routing-information-service-ris/

[2]RouteViews: https://www.routeviews.org/routeviews/

[3]ASRank: https://asrank.caida.org/

3.3 Requirement Analysis

To better understand the requirements of design-markers and analysts, we collaborated with two domain experts working on routing propagation analysis. One expert is a manager of Internet exchange point (IXP), and the other is a researcher in inter-domain routing security. They are proficient in routing analysis and have extensive experience in routing management.

During the requirement analysis, we actively communicated with the experts, demonstrated several prototype systems (e.g., timeline and 3D-based) to them, and collected feedback to refine our design goals. After several iterations, we summarized the experts' requirements and conceived four design goals:

R1: Aligning AS business relationships with BGP update data characteristics. Internet inter-domain routing network resources are allocated by the five Regional Internet Registries (RIRs), exhibiting a centralized hierarchical structure. Routing relationships between ASes can be abstracted into customer-to-provider (c2p), peer-to-peer (p2p), and sibling-to-sibling (s2s). However, the actual routing propagation paths are intricate, and the network topology is dynamically changing. Factors such as link quality, path length, cost, and routing policies all impact the routing paths. Therefore, effectively integrating commercial relationships and routing connectivity features, and optimizing routing paths and AS node mapping methods, should be adopted.

R2: Visualing the hierarchical distribution of regional routing capacities. Regional routing capabilities are crucial for national and regional network security. Effectively presenting regional routing relationships aids decision-makers and network analysts in making informed decisions regarding network layout and management. Experts seek an overview of the routing capabilities of different countries and regions, allowing them to select areas of interest for detailed examination rather than relying on raw data to form an understanding. Therefore, the system should employ regional aggregation to initially display the hierarchical routing capabilities of countries or regions, guiding subsequent analysis.

R3: Supporting multi-perspective interactive exploration of routing behavior. *How regional routing capabilities are reflected in actual routing paths?* An interactive analysis is necessary for experts to gain insights. Aside from analyzing single routing paths, providing multi-perspective analysis of multi-hop routing behaviors and examining multiple routing paths is particularly useful for planning routing strategies. Thus, the system should provide effective methods for multi-perspective interactive analysis.

R4: Allowing multi-granularity analysis of BGP Routing propagation. *Are there any patterns in the routing paths? Which regions have more frequent routing connections?* To answer these questions, experts often cluster routing paths, examine different categories to identify patterns, and ultimately recognize routing behaviors. Therefore, the system should allow multi-granularity analysis, supporting the grouping of routing paths into categories and intuitively differentiating various routing patterns.

3.4 System Workflow

We develop a web-based system, namely AsRelVis, that fulfills the system requirements. As illustrated in Figure. 2, the system mainly consists of three stages: data collection, routing feature modeling,

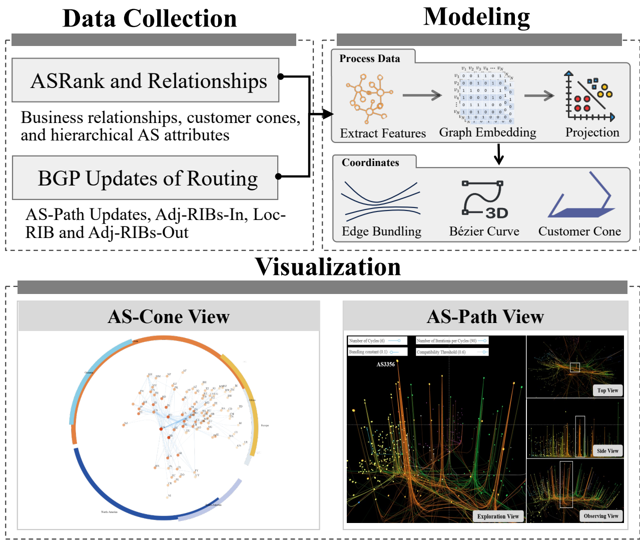


Figure 2: Overview of AsRelVis workflow. Our system consists of three stages: data collection, modeling, and visualization.

and visualization interface. In the data collection stage, we construct a dataset for analyzing both routing business relationships and real routing propagation from RIPE NCC and ASRank. Using hierarchical construction from ASCone data, we categorize routing relationships into distinct tiers. Additionally, leveraging actual routing paths, we delineate routing propagation trajectories. When synthesizing visualizations, we meticulously consider various visualization types, data distributions, and colormaps to ensure effective representation of network regions and routing relationships. We further integrate the geographic latitude and longitude information of ASes to aid in visualizing the spatiotemporal distribution of routing propagation.

In the routing relationship alignment stage, we utilize the geographic and commercial relationship data from the previous stage. An improved Graph Embedding algorithm is employed to enhance the network features [33]. We integrate geographic and hierarchical attributes as virtual nodes into the AS relationship network. Then, we adjust the random walk strategy to train the node2vec model [12], which maps the network node features into high-level vectors. Then, we apply t-SNE to arrange ASes in a 3D perspective, aiming to preserve the commercial relationships and geographic distribution more effectively.

Lastly, in the visualization stage, The ASes and routing paths are presented and interactively analyzed from multiple perspectives, which consists of 1) AS-Cone View, a radial layout-based hierarchical analysis view of regional routing. 2) AS-Path View, 3D perspective view of actual routing propagation paths view. 3) Control Panel, and interaction that aid users in discovery and analysis of routing behavior. We implement the front-end visualization modules in D3.js and Three.js, and integrate them with interactive exploration using Next.js.

4 SYSTEM & METHODS

In this section, we present ASRelVis, a novel inter-domain routing analysis system that integrates four essential design requirements to facilitate comprehensive exploration and understanding of AS relationships in the context of BGP routing. We first introduce the data alignment and modeling methods employed to preprocess and structure the AS relationship data, and then present the visual design incorporated into ASRelVis to support effective exploration and analysis of the inter-domain routing landscape.

4.1 Extracting and Aligning Data Features

AS business relationships reflect the upstream and downstream relationships between ASes in terms of service provision. The routing changes in BGP update, represented by AS path, are based on AS business relationships, while being influenced by factors such as link quality, path length, and throughput. To align AS business relationships with BGP routing propagation features (R1), and visualing the hierarchical distribution of regional routing capacities (R2). We employ the graph embedding method to encode the commercial structure and geographical distribution of ASes in the AS-Rank data into a high-dimensional space. Subsequently, we utilize dimensionality reduction techniques to project node features into space. In the 3D space, we initially project the vectors encoded by graphembedding onto a 2D plane to obtain the coordinates of x and y axes. Then, we map the coordinates of the z-axis based on the hierarchical attributes of AS nodes in commercial relationships to highlight the routing capabilities of different ASes.

During the graph embedding process, we introduce node attributes and network connectivity features to preserve the structural integrity of the network neighborhood while distinguishing geographical distributions. This approach leverages a node attribute-controlled random walk strategy to emphasize the connectivity between upstream and downstream nodes, aligning with the business relationships between any two ASes. In the classic node2vec algorithm [12], assuming node t executes a random walk strategy in the network, with its previous hop being x and progressing to the subsequent node v, with two hyperparameters p and q controlling the direction of the walk, the transition probability $\alpha(t,x)$ for determining the next hop from t to v is as follows:

$$\alpha(t,x) = \begin{cases} \frac{1}{p}, & \text{if } d_{tx} = 0 \\ 1, & \text{if } d_{tx} = 1 \\ \frac{1}{q}, & \text{if } d_{tx} = 2 \end{cases} \tag{1}$$

where d_{tx} represents the cost from node t to node x, indicating distance in unweighted networks. Depending on the value of d_{tx}, different transition probabilities are selected, with p and q controlling the tendency of the strategy's random walk. Specifically, these parameters enable our search procedure to approximate a balance between breadth-first search (BFS) and depth-first search (DFS), thus reflecting a preference for various concepts of node equivalences. To incorporate geographical distribution attributes, inspired by GEGraph [33], we introduce virtual nodes V, which containing geographical information into the network. Subsequently, we introduce a hyperparameter r to extend the calculation of transition probabilities from $\alpha(t,x)$ to $\pi_(t,x)$. The specific calculation is as follows:

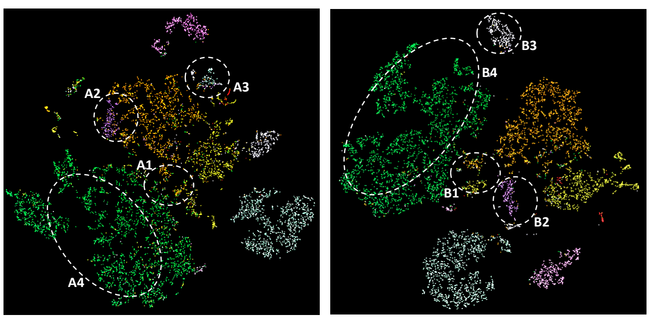
$$\pi_(t,x) = \begin{cases} \frac{1}{r}, & \text{if } t \text{ or } x \in V \\ \alpha(t,x), & \text{otherwise} \end{cases} \tag{2}$$

where the next hop reaching the virtual node or reaching other nodes within the same region from the virtual node with a probability of $\frac{1}{r}$. Parameters p, q, and r can be adjusted according to different application scenarios.

We loaded AS business relationship data from the ASRank dataset (nearly 60,000 nodes with 300,000 pairs of business relationships) and encoded network nodes into a high-dimensional space using both node2vec and node attribute-controlled DeepWalk strategies. Subsequently, we employed t-SNE [2] to project nodes onto a 2D plane. Although node2vec has differentiated nodes from different geographical regions, there are still some regions intertwined in Figure. 3(a). In Figure. 3(A1), the green European nodes and yellow North American nodes lack a clear boundary. Figure. 3(A2) shows the South American nodes intermingled with the surrounding orange North American nodes. Similarly, Figure. 3(A3) demonstrates an ambiguous demarcation between the North American and Asian nodes. Figure. 3(A4) reveals that the European nodes are insufficiently compact.

Embedding based on our node attributes can further effectively cluster geographical information while preserving the structural integrity of the network domain. The algorithm described above focuses on the graph embedding part. To align the dataset of AS business relationships with ASRank data, considering the hierarchical characteristics of ASes caused by AS's customer cone, we can obtain a controllable two-dimensional plane effect based on the attributes of AS nodes themselves. Figure. 3(b) illustrates the performance of different projection algorithms on the network topology. The corresponding visualizations in Figures. 3(B1-B4) demonstrate how our proposed approach effectively mitigates these problems, resulting in clearer separation and tighter clustering of nodes based on their geographical regions.

Furthermore, regarding multi-hop routing path information, we filtered out incomplete routes and aggregated, removing duplicate paths between multiple ASes. The integrated route path was then utilized as the actual BGP route propagation for subsequent route plotting.



(a) Classic Node2Vec algorithm (b) Node attribute-based DeepWalk strategy

Figure 3: The integration of node attribute-based DeepWalk strategy distinguishes the geographic distribution of ASes while preserving domain attributes between nodes. (a) Classic Node2Vec algorithmm, (b) Node attribute-based DeepWalk strategy.

4.2 Visualization

The ASRelVis visualization module consists of Control Pannel, AS-Cone View, and AS-Path View. In this section, we introduce the visual design of each view and the interactions connecting them in detail. ASRelVis integrates both 2D and 3D visualization to provide users with multiple perspectives for analyzing routing propagation, enabling a comprehensive understanding of the complex inter-domain routing dynamics. The Control Pannel (Figure. 1(a)) allows users to specify the essential parameters, including the data source, ovservation points, and the specific time period of interest. The AS-Cone View (Figure. 1(b)) offers a comprehensive overview of the regional AS node interconnections and routing capabilities, enabling users to grasp the high-level structure and dynamics of the inter-domain routing system. The AS-Path View (Figure. 1(c)) enables users to interactively explore the actual propagation paths of routing information between source and destination ASes from a 3D perspective. Users can select specific regions based on the insights gained from the AS-Cone View and examine the detailed routing dynamics within those regions using the AS-Path View.

4.2.1 AS-Cone View

In order to provide a high-level summary **(R1)** and help users perceive the distribution of regional routing capabilities and identify regions of interest **(R2)**, we design the AS-Cone View to visualize country level connectivity using a radial layout.

We emplay a radial layout to represent the routing characteristics of each country, as shown in Figure. 4, inspired by CAIDA's IPv4 and IPv6 AS Core Visualization [16], which utilizes AS rank data. Each node in the visualization represents a country, with the node color indicating the number of AS nodes within that country. Darker colors signify a higher count of ASes owned by the country. The distance of a node from the center of the radial layout is determined by its AS hierarchical structure and routing transit capability, with nodes closer to the center indicating stronger connectivity in inter-domain routing. The angular position of a node corresponds to its geographical longitude, as shown in the outer ring of the radial layout, similar to the Earth's longitude. Starting from the Prime Meridian (i.e., 0° longitude), the layout progresses clockwise to represent Asia, Oceania, Europe, Africa, South America, and North America. Some continents overlap in terms of longitude, which we indicate using different colors in the visualization. The inner ring and the middle section showcase the data variations within each region. For each country, we aggregated all the AS nodes it owns and calculated the country's comprehensive routing capability. A larger Cone value indicates a stronger comprehensive routing capability. For a given country G, let V be the set of all its owned AS nodes. The routing capability of the aggregated AS node, denoted as $\text{Cluster}_{\text{Cone}}$, is calculated as follows:

$$Cluster_{cone}(G) = \log \sum_{v \in V} \text{cone}(v) \tag{3}$$

where v represents an AS node in the set V. When calculating the comprehensive routing capability of each country, we take the logarithm of the sum of the Customer Cone values for all AS nodes in each country to compress the gap between extremely large and small values. This approach helps to highlight the relative differences between countries in the subsequent visualization layout without being dominated by individual countries owning a large number of AS nodes.

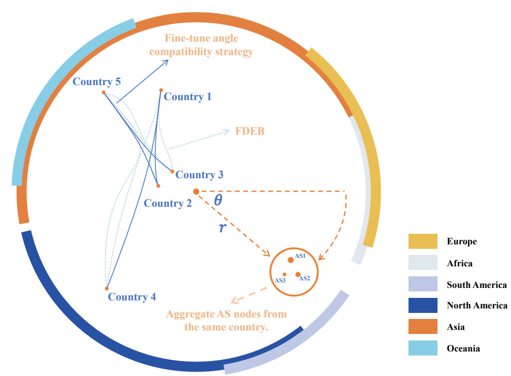


Figure 4: An example of the aggregation and radial layout of AS nodes from the same country, along with the fine-tuning of the angle compatibility strategy.

When laying out node positions, we adopt a radial layout to map the geographical and routing capabilities distribution between countries. For a specific country G, and the AS v with the maximum customer cone value, we can determine its angle $\theta(G)$ and radius $r(G)$ in polar coordinates as follows:

$$\theta(G) = longtitude(v) \tag{4}$$

$$r(G) = 1 - \log\left(\frac{Cluster_{cone}(v) + 1}{Max(Cluster_{cone}) + 1}\right) \tag{5}$$

where $Max(Cluster_{cone})$ represents the maximum value of $Cluster_{cone}$ in this dataset. As shown in Figure.4, our approach calculates the positions of the aggregated AS nodes in the polar coordinate system. By mapping country nodes to angular positions in the polar coordinate system, we can reflect the geographical orientation relationships between countries. The radial layout naturally separates country nodes from different regions, creating a visual grouping effect. This helps observers quickly identify and compare the characteristics and differences of countries in different regions. The routing capabilities gradually decrease from the center outward, providing a reference baseline for comparison of global routing status.

To map the routing propagation relationships between countries, we aggregate actual routing propagation paths and map the routing connections between countries as lines. However, the abundance of complex routing connections can easily lead to visual clutter during layout, such as line crossings and excessive drawing. It is essential to ensure that routing relationships are presented in a clearer and more concise manner. To address this, we employ force directed edge bundling algorithms [14] to optimize the layout. However, bundling strategies based on global force-directed methods may lead to either insufficient bundling or excessive bundling, making it difficult to achieve a clear routing layout effect. We fine-tune the compatibility strategy to achieve an adaptive path aggregation pattern, as described in Algorithm 1. Figure. 5 presents a comparison between the vanilla FDEB method and our proposed approach. The comparison reveals that our methods achieves more pronounced aggregation of routing connections at specific angles, enhancing the clarity and interpretability of the network structure.

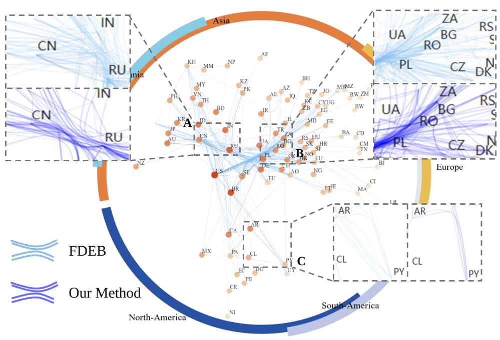


Figure 5: Comparison between vanilla FDEB and FDEB with fine-tuned angle compatibility strategy, the latter effectively aggregates routing connection paths in the routing direction.

4.2.2 AS-Path View

To fulfill the requirement of providing a multi-perspective exploration of routing behavior (R3) and conducting multi-granularity routing propagation analysis (R4). We design the AS-Path View to visualize real multi-perspective routing paths.

BGP update data consists of individual AS paths, with each AS path containing the sequence of AS nodes through which the route passes. In the AS-Path view, we map all AS nodes from the route updates of that time period into a 3D space, where the connections between nodes represent the actual AS paths. The color of nodes represents different continents, where green represents Europe, orange represents North America, yellow represents Asia, etc. The coordinates of nodes are distributed based on the Graph Embedding algorithm, preserving the regional structure. The height of nodes represents the different levels of routing capabilities (AS-Cone) of ASes at various hierarchical levels. Due to the significant differences in AS-Cone values among different nodes, to balance the visual representation, we adopted a technique similar to that used in the AS-Cone view. We calculated the logarithm of the AS-Cone value for each routing node to represent the height along the z-axis.

Another significant visualization challenge lies in the dense intertwining of routing paths resembling flight routes, making it difficult to highlight routing patterns. To mitigate routing overlap, we

Algorithm 1 Fine-tune the Angle Compatibility Strategy

Input: DataFrame AS_{df}, sou, tar, x_{sou}, y_{sou}, x_{tar}, y_{tar}, α, β
sou, tar identifiers for the source and target nodes, representing the relationship between AS nodes.
x_{sou}, y_{sou} are coordinates of the source node.
x_{tar}, y_{tar} are coordinates of the target node.
α, β are angle compatibilities, which we have obtained through multiple experiments.
$link_1$ is set of edges involved in edge bundling.
$link_2$ is set of edges not involved in edge bundling.
function CALCXAXISANGLE(AS_{df}) ▷ Calculate the angle with the X-AXIS.
  for all (sou, tar) in AS_{df} **do**
    $angle_x \leftarrow \arctan(tar.y - sou.y, tar.x - sou.x)$
    $AS_{df}[angle_x] \leftarrow (angle_x < 0)\ ?\ (angle_x + \frac{\pi}{2}) : angle_x$
  end for
  $link_1 \leftarrow AS_{df}[angle_x \in [0, \alpha] \cup [\beta, \frac{\pi}{2}]]$
  $link_2 \leftarrow AS_{df}[angle_x \in [\alpha, \beta]]$
  return $link_1$, $link_2$
end function

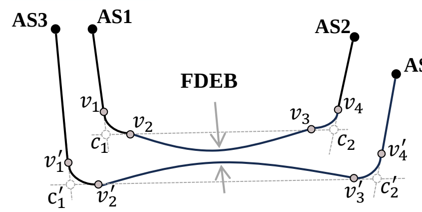
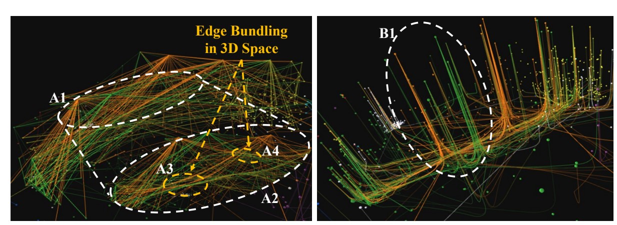


Figure 6: An example of the selection of virtual nodes and control points, along with the force setting.

naturally drew inspiration from the FDEB method for layout optimization. However, even with the application of edge bundling algorithms in three-dimensional space, visual clutter can still occur. As shown in Figure. 6, this approach involves routing paths quickly descending to the z=0 plane from the originating node, then growing upward to the target node just before reaching it. To ensure visual aesthetics, we applied smoothing at the turns of the routing paths. Figure. 7(a) illustrates the layout results of applying the vanilla FDEB algorithm in a 3D space. Figure. 7 (A2) provides a zoomed-in view of the region shown in Figure. 7 (A1). Although Figures. 7 (A3-A4) exhibit edge bundling effects, the overall visual representation remains cluttered, imposing a cognitive burden on the users. In contrast, Figure. 7(b) presents the results of our method after applying smoothing techniques. By descending the network connections to the z=0 plane, as shown in Figure. 7(B1), our approach effectively reduces the visual clutter caused by the intertwining of network connections in the 3D space.



(a) Straight Line and vanilla FDEB in 3D Space (b) Our Methods

Figure 7: Comparison of different AS-path layouts in 3D space. While vanilla FDEB still leads to visual clutter in 3D space. (a) Straight Line and Classic FDEB in 3D Space, (b) Our Methods

5 EVALUATION

In this section, we demonstrate the usefulness and effectiveness of our system through two usage scenarios and a user study. We invited two experts (E1, E2) to conduct the case study using the BGP Update and ASRank data. E1 is the operational manager of an Internet Exchange Point (IXP). E2 possesses in data mining of BGP routing updates, designing algorithms and models to identify and analyze network security events. Additionally, we invited 2 experts and an additional 10 participants from various backgrounds to conduct a user study, evaluating the usability of our system. Dduring the evaluation process, we collected user feedback to further improve our system.

5.1 Scenario 1: Regional-level Routing Distribution

In the first usage scenarios, we demonstrated how users can utilize ASRelVis to explore the routing relationship of countries and regions based on the distribution of AS-Cone, guiding subsequent exploration. We invited expert E1 to conduct the case study. E1 possesses extensive experience in routing management, resource allocation, and troubleshooting. Consequently, he has a profound understanding of system analysis and exploration.

First, E1 randomly selected BGP update data from 10:30 AM to 10:35 AM on February 5, 2018, using the control panel. Subsequently, the system extracted feature information based on the routing update paths and interconnection relationships during that time period and updated the visualization views. Figure. 8 illustrates the geographical connectivity distribution between countries. As shown in Figure. 8(A), E1 observed that the aggregated representation of AS nodes corresponding to the United States is positioned centrally in the ASRelVis visualization, aligning with their expectations. The central positioning of the United States in the visualization reflects its significant role and influence in the global Internet routing ecosystem. As a key player in the development and governance of the Internet, the United States hosts a large number of AS nodes, including many prominent Tier-1 and Tier-2 networks that form the backbone of global connectivity.

From the analysis of routing connections between Europe and the United States, ASRelVis effectively showcases the close interconnection between these two regions. The frequent connection updates and highly interconnected network topology reflect the strong digital ties between Europe and the US. Unlike the United States dominating the North American Internet ecosystem, Europe's Internet landscape is more decentralized, with several major countries having active connections among themselves, as illustrated in Figure. 8(B). This highlights the pluralistic nature of Internet governance in Europe and the cooperation among countries within the region. By visualizing the routing relationships between other continents, such as Asia and Africa, with Europe and the US, ASRelVis reveals the different roles and positions of these regions in the global Internet. While Europe and the US remain the primary sources of interconnection traffic, the network traffic between these continents and Europe/US is not as frequent as that between Europe and the US. This indicates that despite the increasing global interconnectivity, digital divides and regional disparities still exist.

ASRelVis also highlights some interesting regional routing patterns. For example, as shown in Figure. 8(C), the visualization shows relatively close connections between Russia and Asian countries, reflecting its unique geopolitical position as a bridge between Europe and Asia. Similarly, the fewer routing nodes and lower positions of Africa and South America indicate the challenges these regions face in developing global Internet infrastructure, as shown in Figure. 8(D). However, Brazil's prominent position in South America caught the attention of expert P1. As shown in Figure. 8(E), P1 pointed out that the close economic and business ties between Brazil and European/American countries drive the establishment of high-speed Internet connections to meet the demands for data exchange and communication. This insight suggests that international trade and business relationships play a significant role in shaping inter-regional Internet connectivity.

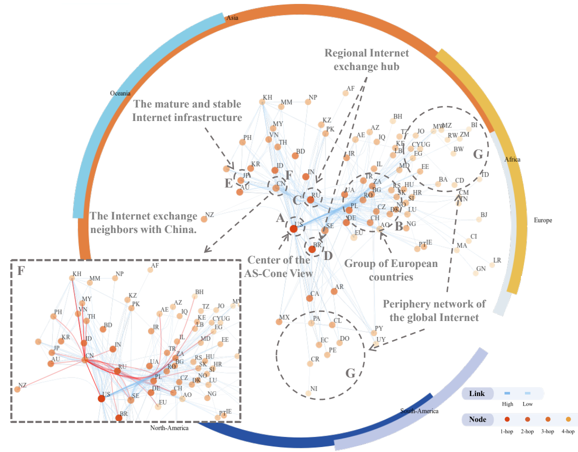


Figure 8: The connectivity and distribution of national and regional routing in the AS-Cone view. ASes at different hierarchical play different roles in the Internet.

Another noteworthy observation shown in Figure. 8(F) is that despite Japan being an economically active region with early Internet development, its Internet relationships and network updates are not the most active. This may indicate the relative maturity and stability of Japan's Internet ecosystem or reflect its unique stance in regional and global Internet governance. Lastly, as shown in Figure 8(G), ASRelVis emphasizes China's leading position in the Asian routing network and its close ties with major international players. This highlights China's significance as a key participant and shaper of the global Internet and its growing digital influence.

Overall, through the analysis of AS-Cone View, such as the routing connections between Europe and the United States, the interconnection patterns of different continents, regional disparities, and the prominence of individual countries, ASRelVis provides valuable insights into comprehensively understanding the global Internet routing ecosystem. It enables users to explore regional interconnection relationships, identify key players, and discover emerging trends. It can also guide users in discovering specific routing propagation patterns by combining the real AS-paths.

5.2 Scenario 2: AS-level Routing Propagation

In the second scenario, E2 combines insights from E1 and utilizes combined visualization and interactive techniques to explore AS-level routing propagation patterns.

From the AS-Path view in ASRelVis, E2 observe that the real routing path connection patterns, which align with the patterns discovered in Usage Scenario 1. The connections between Europe and the United States are very tight, while other continents primarily communicate with the global network through their interconnections with Europe and the US, shown in Figure. 1(c2). E2 dragged and explored the exploration view, where he discovered that the distribution of AS3356's links is very extensive, indicating its robust AS interconnection capabilities, as depicted in Figure. 1(c1). E2 combines the side view and further discovers that routing paths originating from AS3356 form cone-shaped lines, spreading in various directions, shown in Figure. 1(c1). This demonstrates that AS3356 has established a large number of routing connections with most regions globally and has extensive business relationships. E2 added that AS3356 belongs to Level 3 Communications, a top-ranked global communication service provider, and is also the largest peer autonomous system of China Telecom's backbone network.

From the AS top-down view, E2 discovered another interesting phenomenon. There are many AS nodes in South America, but they are mainly internally connected, and their external routes are primarily forwarded through Europe and the US. This echoes E1's inference that this pattern is related to South America's unique geographical and economic conditions. E2 further explored and found that the interconnection between nodes in the north and south of South America is mainly through Brazil's major telecommunications service providers, such as AS16735, AS28329, and AS61568.

In the AS-Path View, we marked China's AS nodes in red. E2 pointed out that currently, the number of AS nodes interconnected between China and the international Internet is relatively small, and the overall Customer Cone value is not high. Among them, the node with the largest Customer Cone value is AS4134, which belongs to the backbone network node deployed by China Telecom in the early stages. A large number of Chinese AS nodes primarily access the global Internet through AS4134. AS4134 mainly establishes peering relationships with important ASes in Europe and the US, such as AS1299 in Europe and AS3356 in the US. These are the largest and fastest-growing communication service providers in Europe and the US.

From the perspective of the entire visualization, North America and Europe's BGP routing capabilities are in a leading position. E2 also pointed out that currently, China's demand for communication with the international Internet is still growing rapidly, and its connection status and interconnection capabilities in the Internet should be further enhanced.

Table 1: User study on effectiveness, visual desitn and usability of ASRelVis. Score (Mean ± STD) for each question are reported. Score distribution maps out the scoring outcomes for each paricipant.

No.	Question	Score	Score Distribution
Q1	The combined 2D and 3D visualization system can assist me in gaining a multi-perspective overview of the regional routing distribution and routing propagation patterns.	4.67 ± 0.47	4 8
Q2	The AS-Cone View helps me understand regional routing capabilities and interconnections between countries during a specific period.	3.75 ± 0.72	1 2 8 1
Q3	The AS-Path View facilitates my exploration of BGP routing behavior from multiple perspectives and granularities during a specific time period.	4.67 ± 0.62	1 2 9
Q4	The FDEB layout with angle compatibility fine-tuning helps to more clearly map the routing connections between countries.	4.33 ± 0.75	2 4 5
Q5	The combined node attribute Graph Embedding method helps differentiate network community structures and maintain the neighborhood structure within communities.	4.08 ± 0.86	1 1 6 4
Q6	The overall system is intuitive and easy to understand.	4.50 ± 0.64	1 4 7
Q7	It is easy to learn and use the system.	4.08 ± 0.86	4 3 5
Q8	I think it is useful to use this system to explore the BGP routing propagation.	3.75 ± 0.92	1 4 4 3
Q9	I would use this system to analysis BGP routing behavior in the future.	4.67 ± 0.47	4 8
Q10	I would like to recommend this system to others who are working on explore routing analysis tasks.	4.50 ± 0.65	1 4 7

1 (Strongly Disagree) 2 3 4 5 (Strongly Agree)

5.3 User Study

We conducted a user study to evaluate the usability of our system and to assess how users perform analysis of routing propagation based on different views provided by the system. Additionally, we aimed to investigate whether the visual design of our system effectively enhances the identification and discovery of routing behavior patterns.

Participants. We recruited 12 participants (P1-P12, seven males and five females, age 22-37, μ =28, σ =4.57) from various domains for the experiment. The participants comprised P1-P2, networking experts who were IXP administrators and managers; P3-P4, researchers in the field of networking; P5, a PhD student specializing in BGP anomaly detection and mining; and P6-P12, master's and doctoral students with expertise in visual analytics. None of the 12 participants are co-authors of this paper.

Procedure. First, participants were asked to provide their basic information, after which they were given a brief tutorial on AsRelVis. Participants were required to complete two practice exercises to familiarize themselves with the system and confirm their comprehension. During the study, participants were presented with a post-interview questionnaire containing questions rated on a 5-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree), to gather their opinions on AsRelVis. As depicted in Table. 1, the questionnaire primarily evaluates the effectiveness, visual design, and usability of AsRelVis. The results and feedback have been thoughtfully summarized.

Results and User Feedback. Drawing upon the user ratings from the questionnaire and feedback obtained during the interviews, we evaluate the visual design, effectiveness, and usability of AsRelVis. Overall, participants got a well understanding of BGP routing propagation through ASRelVis. Most participants noted that the system facilitated their comprehension of the overview of regional routing relationships and the actual routing propagation paths. P2 commented, "I can easily identify the region routing distribution in ASRelVis." As indicated in Table. 1, participants agreed that ASRelVis offers multi-perspective interactivity, aiding users in efficiently analyzing routing propagation compared to the traditional method of directly comparing extensive routing update data. P4 commented that the visualization provided by ASRelVis is clear and insightful, enabling network researchers to systematically and hierarchically analyze routing behavior. ASRelVis eliminates the need to directly handle extensive network data. Moreover, several participants expressed a preference for integrating prior knowledge from network analysis to gain more insightful discovery.

For system workflow, all participants confirmed the effectiveness of using multiple perspectives to explore BGP updates, which they found "intuitive and useful for understanding routing propagation." They also appreciated the idea of radial layout for AS connections between countries. P3 commented, "This tool is pretty helpful for routing monitoring, as it allows for a comprehensive grasp of the current updates in the network space." Furthermore, the participants valued the workflow of selecting specific time periods, examining regional routing relationships overview, and then exploring specific routing paths through the AS path view. They emphasized that this is particularly "important and needed" in real-world work scenarios, as it allows them to retrieve routing paths and quickly understand the overall situation from a global to a detailed perspective.

For visual design and layout, the most of the participants agreed that the overall visual design of ASRelVis is intuitive and easy to understand. Regarding the presentation of multiple perspectives in the AS-Path view, participants believe that offering various viewing angles assists users in understanding and discovering patterns in routing behavior. However, sometimes participants lacked familiarity with the interaction in the 3D view. For instance, P7 found that the dragging and zooming functionality in the AS-Path view was not very user-friendly, making it difficult to adjust to a suitable viewing angle. The participants agreed that the node-link layout in the AS-Path view, along with the aggregation and optimization of routing propagation paths, to some extent alleviated visual clutter, as shown in Table. 1.

For usability, they also appreciated the system's filtering and interaction features, which facilitated a more flexible exploration of routing updates across different time periods. P8 suggested that comparing routing updates across different time periods would support users in routing analysis more effectively. Lastly, all the participants expressed their willingness to recommend the system to others who are working on explore routing analysis tasks in the future. P11 stated, "exploring the multi-perspective routing propagation in the system was immersive, and I enjoyed the process."

For suggeations and improvement, P1 suggested saving selected templates for future reference, adding more time intervals and node metadata for comprehensive routing propagation summaries, with a focus on abnormal routing behavior. P2 proposed real-time data for viewing the latest routing trends and advanced strategies for routing propagation trajectory layout. Participants with visualization backgrounds expressed concerns about edge bundling algorithm efficiency and data rendering pressure. P9 and P10 recommended using faster edge bundling algorithms like FFTEB [23] and improving rendering strategies for the 3D view as time periods and data complexity increase.

6 Discussion and Future Work

In this work, we present ASRelVis for understanding and exploring BGP routing propagation. We preliminarily validated the effectiveness of the workflow and visual interface, through two use scenarios and an expert interview.

Multi-perspective routing exploration and analysis During our development, we faced challenges and limitations and identified extensions that could improve our approach. Processing large BGP update data posed a significant challenge. Queries spanning long time periods across all collectors necessitated substantial downloads and computational power to ensure a responsive web service. Additionally, data access limitations precluded querying for specific locations, meaning users couldn't obtain data solely for particular geographical regions without downloading data from all collectors. Moreover, the accessible time frames were discretized into 5-minute intervals for RIPE and 15-minute intervals for Routeviews. Due to the substantial volume of BGP route update data within short timeframes, our current work can support routing updates for small time ranges. In the future, we need to further optimize data collection and processing, as well as refine layout methods to address challenges such as node crossings and rendering pressures. By observing different AS network graphs, we found that the actual network connections between organizations are not always optimized for the shortest geographical paths, but are driven by various factors such as economic, political, or environmental considerations. In addition, the routing paths between different IP blocks owned by the same AS organization may vary. Designing more granular perspectives to explore routing update patterns is an interesting direction for future research.

Generalizability and Scalability The proposed workflow is capable of multi-granularity network exploration and analysis tasks. For example, for network path data, ASRelVis can provide an overview of specific community connections. Then, the multi-perspective 3D view can be revised to enable detailed analysis of propagation paths. For tasks such as routing behavior analysis and routing anomaly detection, the network aggregation granularity can be flexibly defined and combined according to different levels of analysis to analyze routing patterns. Additionally, considering that path analysis is a fundamental task in network exploration, ASRelVis is transferable to a wide range of applications and network types. For instance, domains like social media networks and citation networks share similar requirements for constructing models to analyze pathway propagation and interactions from multiple perspectives.

Limitations and future works. Currently, to discern specific regional patterns, we aggregate all AS nodes within the same country to analyze the routing distribution between countries and regions. However, the granularity of node aggregation may vary for different analysis tasks. In future iterations, we can provide customizable aggregation granularity and rules to facilitate flexible exploration of regional distribution. Additionally, the system currently supports analysis for a single time slice, lacking the capability to compare the current routing patterns with historical routing paths. In future work, developing a module for comparing routing changes over time could be considered. Integrating all the valuable suggestions from the different user groups we gathered will be our next step. We are going to improve our algorithm to accommodate large volumes of routing nodes and path data by adopting techniques such as FFTED and parallel computing to enhance the performance of FDEB. Furthermore, we will further adjust the edge bundling strategy to optimize the layout of routing connections.

7 Conclusion

In this work, we propose ASRelVis, an effective visual analytics system facilitating the exploration of BGP routing update data. Through collaboration with domain experts, we identified requirements and tasks, resulting in ASRelVis comprising three views within a multi-perspective analysis workflow. We employ a fine-tuned FDEB algorithm with customized angle compatibility strategies and improved graph embedding methods incorporating node attributes to visualize regional routing distribution and real routing propagation paths. Two user scenarios, along with user feedback and a user study, demonstrated ASRelVis' design and effectiveness. Positioned as a prototype for domain experts in inter-domain routing analysis, ASRelVis combines 2D and 3D visualization techniques to explore routing behavior patterns. It reveals connections between regions, the roles of key AS nodes, and intra- and inter-regional route propagation characteristics. Expert insights further enrich understanding of driving factors, including economic, geographical, and policy factors.

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