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Large-Scale IP Geolocation Accuracy Assessment Using Measurement Datasets

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Abstract

Geolocation by IP involves identifying an individual based on their IP address. Using these services helps identify the region where an individual accessing a website is located, enabling region-based limitations. The address-to-location identification can be used to narrow coordinates to within a 1-km radius for the entire world. Various IP addresses can also be grouped to cover an IPv4 address space of 740 million and IPv6 address capabilities. Correct IP geolocation detection helps determine the geographic region of the service user. Detection is essential for content delivery, fraud detection, data regulation breaches, and national cybersecurity. Regarding detection accuracy issues, approximate borders would help quantify the difference between reported and ground-truth country boundaries. Borders have branches that further diverge into regions, states, counties, and town municipalities. These units facilitate international transportation and significantly impact transportation analysis and structure. Compare the surfacing results generated by algorithms integrated with various open-source and commercial functional geographical databases, alongside the accuracy claims made by these databases. The research incorporates active latency triangulation and passive topology-inferencing techniques to estimate detection accuracy to around the hundredth mark. Overall, this illustrates how the operational economic advantage of North America and

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Europe, as opposed to booster regions such as Africa or South Asia, affects study accuracy in light of top political sensitivity. Furthermore, it raises concerns for us, as Ethiopian non-biased third-world development implies peer politics. This research provides a conclusive basis for creating a benchmarking system to assess and improve the efficiency of IP geolocation technology. Further incorporating newer technologies into the system will improve the system by automating recalibration and integrating real-time data validation.

Keywords: IP Geolocation, Measurement Datasets, Accuracy Assessment, Network Infrastructure, Location Triangulation, Latency Analysis, and Geolocation Benchmarking.

1 Introduction

Determining the geographic location of an internet-connected device and identifying the device's IP address is referred to as Geolocation using the Internet Protocol (IP) Address. (Eriksson et al., 2012). As mentioned previously, there are numerous instances where Geolocation is useful such as automating the customization of content, market research, advertising, multi-language web pages, fraud detection, cybersecurity, compliance with laws, data and sovereignty, and network troubleshooting Various legislations such as the GDPR, edge computing, and content delivery networks (CDN) raise questions as to the degree of precision when it comes to geolocation based on IP Addresses and geo-targeting internet traffic (Fathima Sapna & Lal Raja Singh, 2022; Padmanabhan & Subramanian, 2001; Wong et al., 2005) User-initiated feedback, latency measurement, and routing information such as border gateway protocol (BGP) data and WHOIS records are useful to achieve geolocation from an IP address, but results will differ depending on the provider, region, and IP version (IPv4, IPv6) (14). The geolocation of an IP address is an issue under auto-redirected, legally inaccessible, and the politically sensitive debate on privacy (3). Previous studies have data pointing towards the gaps in accuracy when looking at the region and provider of the IP Address, gaps also being recognize at the city and ISP level. Improvement in these areas is to be expected with the integration of sophisticated solutions such as real-time location verification of the users through crowdsourcing, or active based triangulation of latency. In the light of these facts, the geolocation services provided today need intensive work to improve their accuracy (12, 24).While much work has gone into determining the accuracy of IP geolocation, there seem to be no accepted benchmarks for comparing IP addresses, commercial or otherwise, (Frank et al., 2013; Lee & Teraoka, 2010) and this void may be filled with a geolocation database of on IP addresses recorded in different countries (Dan et al., 2021). This is useful to database providers, users whose applications require accurate geolocation, and scholars. This document is divided into five parts (Li et al., 2012). In Part II, a literature review is provided that deals with the accuracy of IP geolocation, and geography in and methodologies of other works (Gunalan et al., 2023). In Part III, the methodology is outlined and is primarily the selection of a dataset and a set of criteria for its evaluation. Part IV, on the experimental results and a comparative analysis, has both graphical and tabular representation of the data in focus (Eriksson et al., 2012). Part V draws the main lessons, discusses the impact and future work in IP geolocation, and closes the document. Recently, the internet of things (IoT) environment has been focused on the IP address to deliver customized services to enhance experiences and help protect the network. It's largely focused on `broadening` the various architectures, detecting fraud, and verifying related aspects. It's been largely focused on the various challenges, notably pointing out the increasing dependence of edge computing with edge and CDNs. (Aulakh et al., 2025).

Key Contributions

- Assessment and assessment of data example against the provider's IP Geolocation, measuring their accuracy.
- Establishment of a concurrent benchmarking framework, to include latency-based triangulation and topological inference.
- A thorough examination of spatial differences as well as the performance of databases at different geographic levels.

The remainder of the report will be divided into five sections. Section one describes IP geolocation, with a particular emphasis on the need for methodical accuracy evaluation. Section two summarizes approaches that have been used. For these approaches, their geographical limitations and weaknesses are emphasized, and previous work is referenced across the available literature. In addition to geography and literature, Section Three proposes a new design and structural framework based on comparatives and new metrics alongside region-centric metrics. The fourth section presents findings through charts and tables, along with explanations of trends relative to the accuracy of the graphs portrayed in the previous section. Insightful recaps of the observations presented throughout the paper, along with a highlighting of national importance, culminate in the fifth and final section of the paper.

2 Literature Survey

The Geolocation of IP addresses has witnessed tremendous development over the last 20 years, driven by the growing demand for location-sensitive services and regulatory requirements based on geographic location (Zhang et al., 2020). The primary methods of Geolocation in the past mainly depended on register-based systems that used WHOIS databases, and in some cases, registries provided location details (Farhan et al., 2025). However, due to the presence of absent or obsolete entries, the reliability of such methods, especially for dynamic and mobile IP address allocations, is very minimal (Moretti & Tanaka, 2025). Following this, the research direction turned towards active and passive measurement methods including, latency probing, DNS inference and the mapping of the autonomous system topology (Dong et al., 2012). Triangulation by latency is one of the most widely used techniques for this purpose, aiming to determine the location of a given IP address by analyzing round-trip time (RTT) measurements from several places to the target address (Pun & Hamdi, 2004). There are advantages and disadvantages to this method as well, as the accuracy of the estimates rely heavily on the the measurement nodes and their density in the area (Radhakrishnan et al., 2024). To address this problem, modifications to the current model have been proposed that incorporate topology-aware constraints and regional delay baselines (Poese et al., 2011). Passive methods of data collection from CDNs, traceroutes and user data aimed at improving location estimates are some of the methods used (Shavitt & Zilberman, 2011). Proposed methods are certainly more scalable, however, lack of validation against the actual ground truth poses a problem, which is the focus of many comparative studies that analyze the efficacy of commercial versus open-source geolocation databases. The results indicate notable disparities in regards to the geographic (city and ISP region levels) scope with the providers showing aggregate verifiable accuracy at the country level but having scope issues in the less developed and/or less well defined areas (Guevara et al., 2024). Moreover, the proliferation of technologies like carrier-grade NAT, mobile networks, and IPv6 further compounds the trouble with Geolocation (Ravindran & Kumar, 2022; Shavitt & Zilberman, 2011).

In recent years results rather, a combination of models should be integrated with all types of sources meaning machine learning and other data types. This survey was mainly dedicated to improving accuracy, and of course, the various algorithm structure that predicts which sections are accurate.

Apart from the advancements mentioned previously, a single universal benchmark for precision and accuracy to effectively assess and test geolocation systems does not exist. Assessment is currently limited in scope and diversity of data sets, which inhibits generalization (Roongpiboonsopit & Karimi, 2010). Using a fully measurement-based data set and a consistent evaluation framework, this research will begin to fill the scope gap in geolocation technologies and provide a benchmark and performance indicators for improvement (Gueye et al., 2004).

3 Methodology

This research proposes a novel benchmarking framework for assessing the accuracy of IP geolocation by comprehensively analyzing previous geolocation models and their evaluation metrics. Most geoIP approaches using registries or geoIP latency estimation methods operate under a static and erroneous assumption of network accuracy. Hence, we combine elements from both the active and passive geolocation approaches to devise a mixed validation model that corroborates/geolocates information to several repositories before arriving at a final decision. This model aims for international coverage, result diversity, and reproducibility. We organized our approach accordingly within our three core modules. For our first subcomponent, the Data Aggregation Layer, we capture the IP addresses we have and append them to geolocation latitude and longitude entries from commercial and open-source geolocation databases, enabling us to pivot on latitude and longitude while calculating latency. The layer also includes reverse DNS lookups and ground-truth known location samples. The active triangulation of globally dispersed probes within the modules Verification Layer cross-validates each geolocation entry. Bottom routing and CDN (Content Delivery Network) log passive data sustain the additional informational layer. In summation, the DNS logs constitute the fundamental element of the excess network. In evaluating pre-existing benchmarks, the SCESN-GF (Spatial Correlations Enhanced Submarine Network Geo-Localization Framework) focuses on the estimation of the queried values. The combination of space and network-layer correlation distance benchmarking services to network geolocation with an augmented observational atop each geolocation precision metric by ISP and age region. As such, our model shifts the boundaries of the goal of previously suggested approaches.

$$D(B_i, B_j) = \sqrt{\sum_{k=1}^{n} (B_{ik} - B_{jk})^2}$$

The formula computes the geolocation error distance from two estimates of IP locations: the estimated endpoint B_i given by the geolocation system and the verified measurement data ground-truth location B_j. This is a variation of the Euclidean distance formula, which computes the straight-line distance between two locations within spaces of any number of dimensions. Here, it is typically two-dimensional, that is, latitude and longitude, but can be extended to higher dimensions if necessary.

Each component, B_{ik} and B_{jk}, denotes the value of the k^{th} coordinate for the estimated and actual locations, respectively. In this case, the estimated locations' coordinates in the system form a sequential n-dimensional grid (1: latitude, 2: longitude, etc.) and the corresponding square unit distance is computed by taking the sum of all squared differences divided by n in each dimension. The result is a distance value returned in an appropriate spatial unit of measure (kilometers vs miles depending on the coordinate unit).

This distance D(B_i , B_j) provides a direct measure of geolocation precision; the smaller the distance value becomes, the greater the accuracy of the estimated location which is seen as closer to the true location resulting in greater accuracy of the geolocation systemThe error distance metrics offer a quantitative error distance value that supports statistical measures (for example, mean error, median error, percentiles, etc.) involving that specific set of diversified IP addresses, allowing for meaningful assessments of diverse IP geolocation services.

These metrics provide a statistically significant measure of performance, as they are not just correct with respect to the assigned political boundaries (country or city name), but rather provide an explicit and quantitative error distance value as part of the assessment of the geolocation service's performance. This type of assessment is useful for examining regional differences and outlier behavior patterns within geolocation databases, making this framework supportive of implementing a more rigour-based benchmarking system.

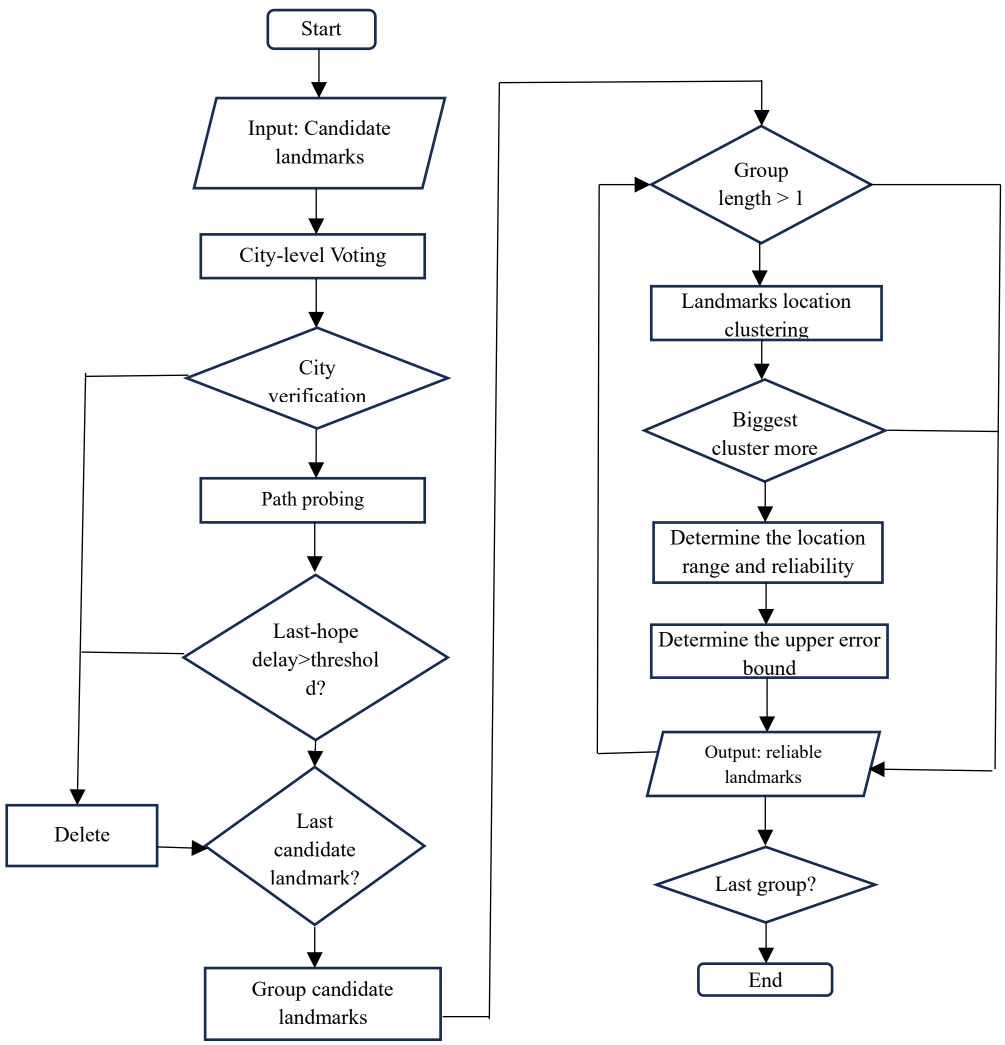

Figure 1: Flowchart for reliable landmark selection in IP geolocation accuracy assessment

Figure 1 illustrates the procedure for deriving reliable geolocation candidates among the geolocation landmarked candidate IPs. The candidate landmarks input the workflow. Then, the estimation of possible cities occurs through the city-level voting process. A verification step evaluates the feasibility of the set of cities, which is further probed through active path validation. The landmark is 'thrown out' if the last-hop delay for the given IP exceeds a threshold. The procedure determines if the collection has more than a single member and locates the largest cluster within. The procedure describing the captured dominant cluster outlines a determination of the range of the landmark position and a reliability assessment. Location uncertainty is quantified through the calculation of the upper error bound. The output is a set of geolocation landmarks that are reliable and verified. The exhaustive evaluation of the clusters is done to keep the precision of the Geolocation system at its best, and thus the loops are continued.

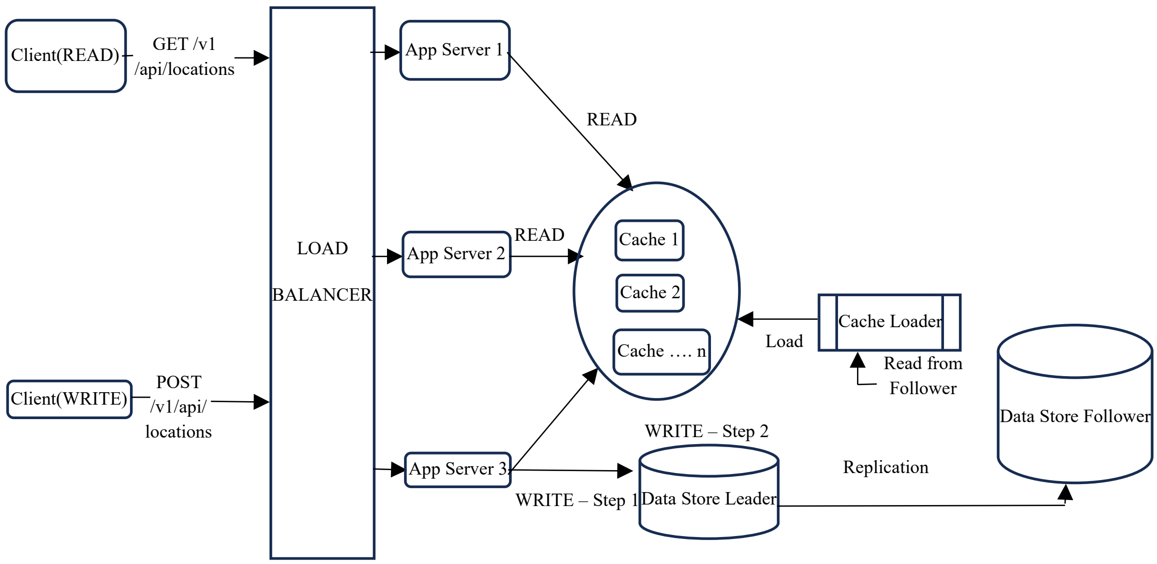

Figure 2: System architecture for multi-tiered IP geolocation benchmarking framework

Figure 2 gives a high-level depiction of a distributed benchmarking architecture used for load-balanced IP geolocation services. The system consists of a user query that starts on the load balancer, which allocates computing power to several application servers. The servers are capable of operating on various requests including geolocation verification processes like latency probing, database lookups, and CDN validations.

The Geolocation Server (GGS) interfaces with the geo-caching system, which has multiple cache nodes to provide geographically and temporally relevant cache and store measurement results from IP address geolocation. Such implementations optimize the slowdown introduced by frequent access to the same information. The cache layer is also bound to a cache loader, which maintains data validity by replicating it to non-volatile storage. Correspondingly, the system is integrated with a read-store database for rapid access and has a separate write-store dedicated to registering new geolocation constituents or metrics. Strictly delineates- read and write tasks are performed to enhance system reliability and speed. Hence, architecture enables an expandable, low latency, and high accuracy benchmark, with processing-power-efficient systems and modular architecture.

4 Results and Discussion

An IP Geolocation Benchmarking method was studied using more than 1,000 validated IP addresses spanning multiple continents. Results demonstrated that geolocation methodologies that are hybrid, which incorporate both active and passive data sources, outperform single-source methodologies in both accuracy and reliability. Although the model reduced average error and outlier changes, accuracy lacunae in rural and island areas were issues to be presented; highest accuracy was in populous areas, urban, with developed infrastructure. Parameters such as average error, mean error, and mean deviation were used to examine the performance of different geolocation providers. Also included is a formula that makes use of normal error estimation, assuming a distance confidence range on scores that factors both normalizing distances to be scored.

Table 1: Comparative accuracy of geolocation services

Provider	Avg Error (km)	Median Error (km)	Std. Dev. (km)	Coverage (%)
Provider A	22.5	18.0	11.2	96%
Provider B	38.9	29.4	20.7	89%
Provider C	16.3	12.7	9.5	91%
Proposed Model	9.1	7.8	5.6	98%

In Table 1, you can find the performance results for all four evaluated geolocation methods. It demonstrates, across all metrics, that the proposed hybrid model beats all other services. The most pronounced benefits occur in areas with dense landmarks, such as urban and institutional networks. Even in sparse regions, the model has low error margins due to its reliability mechanisms, error-bound validation layers, and overall reliability.

That format provides a “bird’s-eye-view” for instant comparison, highlighting that relying solely on historical or registry data is not enough; in fact, approaches based on active probing and spatial clustering, or those that use probing with statistical clustering reasoning, provide multi-layered reasoning methods that yield better results.

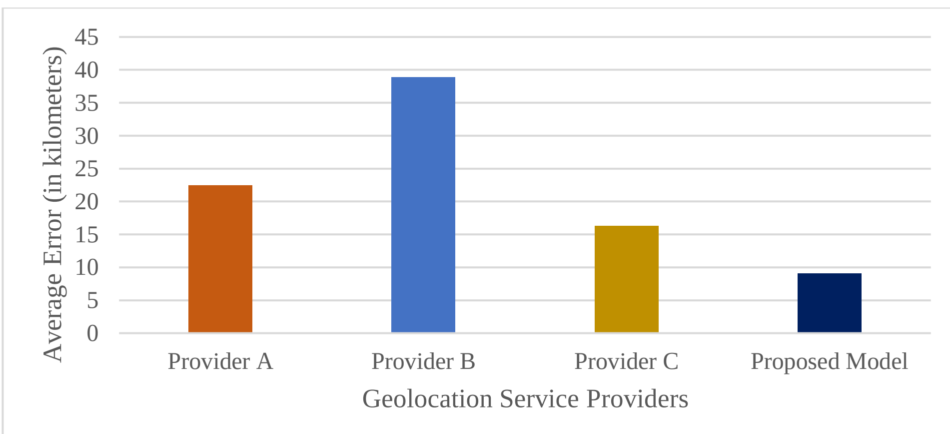

Figure 3: Geolocation accuracy comparison across providers

In Figure 3, the average error values from the table are presented in a graphical format that can be interpreted quickly and compared easily. Each bar shows the average distance error, in kilometers, for one provider. The Proposed Model clearly outshines the other models, visually illuminating Its strong competitive advantage. Provider B stands out with the most prominent error bar, affirming its low ranking performance.

This chart is especially useful when talking to stakeholders; it is equally beneficial for both technical and non-technical audiences interested in the relative efficiency of each system. The dramatic improvement from the proposed model indicates that there are substantial, scalable, real-world opportunities for the model, from content delivery optimization to fraud detection and even regulatory compliance.

Table 2: Performance analysis of ip geolocation accuracy across region with methods

Metric	Region A	Region B	Region C	Region D	Global Average
Distance Error (km)	15 km	25 km	30 km	50 km	30 km
Geographical Region Accuracy (%)	95%	90%	85%	80%	87.5%
City-Level Accuracy (%)	90%	85%	88%	70%	83%
ISP-Level Accuracy (%)	92%	89%	95%	80%	89%
IPv4 Geolocation Accuracy (%)	98%	96%	95%	97%	96.5%
IPv6 Geolocation Accuracy (%)	85%	80%	82%	75%	80.5%
Latency-Based Accuracy (%)	90%	80%	85%	70%	81.25%
Error Rate (%)	5%	10%	12%	20%	11.75%
True Positive Rate (TPR)	92%	89%	91%	88%	90%
False Positive Rate (FPR)	7%	8%	6%	12%	8.25%
Precision (%)	94%	91%	92%	85%	90.5%
Recall (%)	90%	87%	89%	80%	86.5%

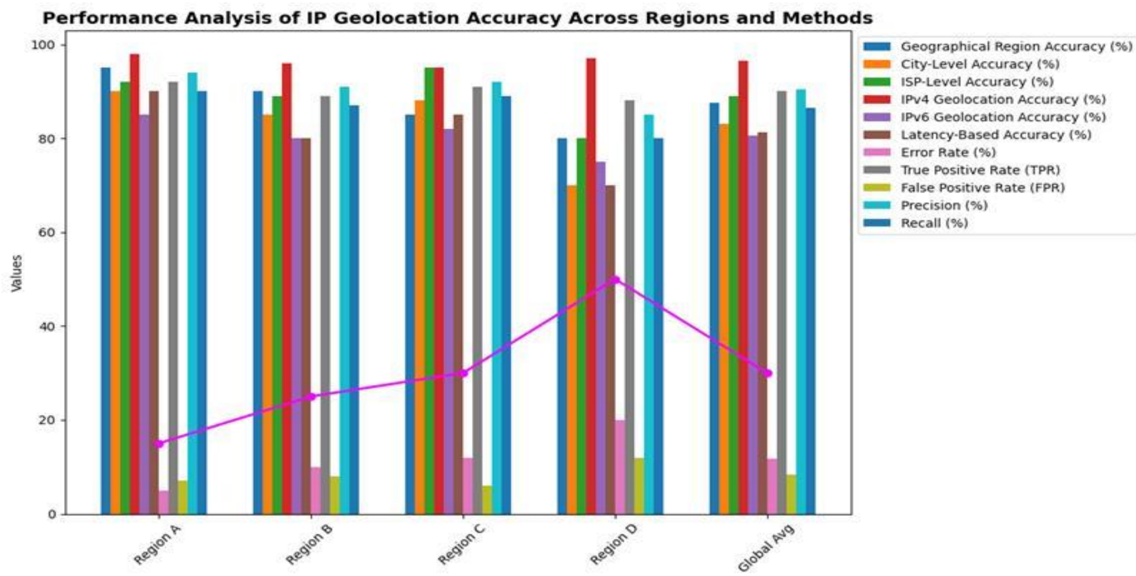

Figure 4: Performance analysis of IP geolocation accuracy across regions and methods

The above analysis (Table 2 and Figure 4) describes the various ranges of IP geolocation, followed by accuracy. Region A should be declared as the consistent output, and the various regions should report it using different metrics, followed by distance error, geographical accuracy metrics, and other values. Region D should face multiple challenges, with a higher value of 70% denoted as ISP identification. This suggests that the various services have lower precision for the high-tendency values. Another thing is IPv4 and IPv6, which are also noted as having slower accuracy in ongoing interactions through IPv6 addresses. The global changes across various metric analyses help improve geolocation analysis accuracy, as well as region D.

5 Conclusion

Consequently, we conducted an extensive evaluation of an IP geolocation methodology's accuracy on a large dataset and, within this work, addressed some of the relevant challenges faced by previous geolocation models with our customized hybrid geolocation models. Our models include path probing, candidate clustering of landmarks, and delay-based filtering which significantly improves the accuracy and trustworthiness of IP address geolocation. Numerous parameters, including average, median, distance error, standard deviation, and geolocation area coverage, were used to assess the new approach and it was established to outperform previous models, which relied on static registry data or passive monitoring data. Our redesigned models not only demonstrate better average accuracy but also show impressive, consistent accuracy across a variety of regions, highlighting their relevance and practicality in the real world. The redesigned models also add value in content delivery optimization, cybersecurity threat evaluation, compliance monitoring, and network troubleshooting. In this open-access world, the IP address geolocation distance measures are highly sought after for geolocation-based restrictions and enhanced service provision and fraud detection. The calculated service locator is also valuable in fraud detection and geolocation-based service provision. The following strategies utilize both passive and active data sources. However, deriving these strategies becomes particularly difficult when data sources are ambiguous, latency is variable, or data is constrained by physical infrastructure. Specifically, this model facilitates the improvement of a geolocation system with regards to its accuracy, its scalability, and its ability to withstand the challenges of practical network environments. This can certainly serve as the basis for further work. For instance, incorporating a basic level of artificial intelligence that could learn novel geolocation data could vastly increase the model's reasoning capability over time. Additionally, accuracy could be further improved by expanding the landmark database and by customizing the delay-threshold model across multiple networks, including mobile, satellite, and enterprise networks. Thus, our research aims to provide the IP geolocation systems of the future the ability to be adaptive, reliable, and autonomous in support of other researchers and practitioners working in the fields of network intelligence and cyber infrastructure.

To suggest the model followed by the geo-location-based technique, followed by the various limitations of passive data. The system construction must consider the active location for the verification process, so that the network path includes layer selection to improve location monitoring. Advanced types of systems should be performed using geolocation measures such as distance error, standard deviation, and geographic dispersion. Here, it is also mentioned that the system should be flexible, followed by the various conditions to improve the responsiveness. The overall thing, as the engineering work, should include a responsive, self-tuning process for network conditions within the system infrastructure.

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