A Detailed Path-latency Model for Router Geolocation

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***Abstract*—This study outlines two novel techniques which can be used in the area of IP geolocation. First we introduce a detailed path-latency model to be able to determine the overall propagation delays along the network paths more accurately. This knowledge then leads to more precise geographic distance estimation between network routers and measurement nodes. In addition to the application of the detailed path-latency model, we describe a method which utilizes high-precision one-way delay measurements to further increase the accuracy of router geolocation techniques. The precise one-way delay values are used as a "path-constraint" to limit the overall geographic distance between the measurement nodes. The approach introduced in this paper can be used to localize all the network routers along the network path between the measurement nodes and can be combined with other existing geolocation techniques. The introduced techniques are validated in a wide range of experiments performed in the `ETOMIC` measurement infrastructure.**

I. Introduction

New location aware applications like e-commerce, censorships, web site traffic monitoring and targeted advertisements have been appearing since the last years, which directs the attention to IP geolocation. The localization of IP addresses became important in scientific areas as well, e.g. to visualize the results of Internet measurements. Nevertheless, determining geographical location of Internet hosts by a single IP address poses many challenges, since there is no direct relationship between the IP address of a host and its geographic location.

Many of the existing geolocation services are based on databases which store organizational information assigned to IP domains, or try to infer location information from DNS names. Usually the accuracy of these services is insufficient due to the lack of reliable information. To overstep the uncertainty of techniques based on geolinguistic approach, recently active geolocation techniques have emerged. These techniques make an attempt to approximate geographical distances from delay measurements.

This paper outlines novel techniques which can be used in the area of geolocation and can be combined with other existing methods. First we introduce a novel detailed path-latency model to identify the contribution of various phenomena to the packet delay. Among these contributions we determine the ones which are related to the geographical distance that a packet travels. Our model, instead of handling the packet delay as an irreducible unit, decomposes the overall path-wise packet delay to link-wise components like the processing delay, propagation delay and even ICMP Echo Reply generation time. In this way we are able to approximate the overall propagation delay along the measurement path. The knowledge of accurate propagation delay values then leads to more precise geographic distance estimations between measurement nodes (also called *landmarks*) and network routers. By using the basic multilateration technique the estimated distance values can be applied to infer the geographic location of Internet hosts.

It is possible to refine the path-latency model by using one-way delay values as well. Taking one-way delays into account by additional constraints, one can significantly improve the accuracy of router localization. Nowadays, just a few infrastructures provide this service, but we believe that in the future Internet the network nodes will be capable of measuring novel network metrics including one-way delays. In our case one-way delays are measured between the landmark nodes and provide new constraints by limiting the physical lengths of the overall network paths.

This paper aims to present the efficiency and usefulness of a detailed path-latency model in geolocation techniques. We also show how the extra information provided by precise one-way delay measurements can improve the accuracy of location approximation. Finally, the performance of the presented methods are investigated in real world experiments performed in the `ETOMIC` measurement infrastructure [1], and then the results are validated in the `GÉANT2` research network [2].

The rest of the paper is organized as follows: in Section II we briefly overview the prior geolocation methods including constraint and topology based methods. Section III describes the detailed path-latency model which constitutes the basis of our geolocation technique. The application of this model for geographical distance approximation is presented in Section IV. Based on this distance approximation method we introduce several geographic constraints including the novel one-way delay based "path-constraint" in Section V. The details of the data collection process, including the description of the performed experiments can be found in Section VI. In Section VII we present a complete performance analysis focusing on the accuracy and consistency of the location estimation.

II. Related Work

During the recent years several geolocation techniques have emerged, all of them aim to give an accurate approximation of the location of network hosts which are not known *a-priori*. Many of these techniques use passive methods like *Whois*

TABLE I

SHORT EXPLANATION OF NOTATIONS USED IN THE PAPER.

notation	short explanation
D_{pc}	processing delay
D_q	queuing delay
D_{tr}	transmission delay
d_h	overall packet delay on a single hop
D_g	ICMP Echo Reply generation time
$D_{pg}(\mathbf{a}, \mathbf{b})$	overall one-way propagation delay from **a** to **b**
$D_{pg}(\mathbf{a}, \mathbf{b}, \mathbf{a})$	overall round-trip propagation delay between **a** and **b**
$d(\mathbf{a}, \mathbf{b})$	overall one-way delay from node **a** to node **b**
$d(\mathbf{a}, \mathbf{b}, \mathbf{a})$	overall round-trip delay between **a** and **b**
$s(\mathbf{a}, \mathbf{b})$	geographical (great circle) distance between two nodes
r	velocity of signal propagation (in c units)

databases [3] and *DNS* names [4] to determine the location of a given router. These databases map large IP blocks to geographic locations which leads large geolocation error in case of geographically dispersed address blocks.

Some proposals try to overcome these limitations. *IP2Geo* [4] contains a measurement based approach *Geoping*, which tries to approximate the geographical distance of network hosts on the basis of the packet delay measurements. A more mature approach is the simultaneous application of several delay constraints to infer the location of a network host. This is done by *constraint-based-geolocation (CBG)* techniques [6]. CBG introduces a triangulation-like method to combine the distance estimates from all landmarks. To estimate delay-distance relation, each landmark measures the delay from itself to all the others. From these inter-landmark measurements CBG can determine the *bestline* by data fitting [6]. In general, each delay measurement defines a circle around the landmark from where the delay was measured. The possible locations of the target node are determined by intersecting all of these circles. Most of the time this intersection produces a region in which the target node must be located.

Another technique is where the topology information and latency measurements are used in the location estimation. This method type is called *topology based geolocation (TBG)* [7]. TBG localizes all the intermediate routers between the landmarks and the target node. This approach is based on link-latency estimations and on precise topology discovery. The basic tools of this method are `traceroute` and interface clustering applications.

In the following we introduce a method that combines CBG and TBG techniques. Opposite to the prior works, we use a detailed network model to determine geographical distances from the landmarks and we introduce new types of geographical constraints using one-way delay measurements.

III. PATH-LATENCY MODEL

The delay experienced by a packet as it passes through the network is a sum of contributions from various phenomena. Based on [8], [9] and [10] the packet delay on a single hop is divided into four major classes: processing delay (D_{pc}), queuing delay (D_q), transmission delay (D_{tr}) and propagation delay (D_{pg}). Since the packet delay is an additive metric, the per-hop delays can be summed up for each hop along the path. By this, the overall packet delay of a given packet can be written as:

$$d(\mathbf{s}, \mathbf{d}) = \sum_{i=1}^{H} (D_{pc}^i + D_q^i + D_{tr}^i + D_{pg}(\mathbf{n_{i-1}}, \mathbf{n_i})), \qquad (1)$$

where the number of hops is denoted by H, and the measurement path is $\mathbf{s} = \mathbf{n_0}, \mathbf{n_1}, \dots, \mathbf{n_H} = \mathbf{d}$. From the above expression the only contribution that is related to the geographical distance is the propagation delay.

Usually the overall packet delay $d(\mathbf{s}, \mathbf{d})$ is used to estimate the delay parameters, since in general it is not possible to directly measure the propagation delay. To determine the value of $D_{pg}(\mathbf{s}, \mathbf{d})$ overall propagation delay, we have to subtract the different kind of delay quantities from the overall packet delay. In case of no queuing the contribution of the queuing delay is neglected $D_q^i = 0$, while for a given probe packet size the contribution of the transmission delay is constant for all the probe packets at a given hop. Since we have no detailed information about the delay values at individual routers we treat the processing and transmission delays with a constant value $D_{pc}^i = D_{pc}$ and $D_{tr}^i = D_{tr}$ for each $i = 1 \dots H$ hop. In this case the overall propagation delay between source $\mathbf{s}$ and destination $\mathbf{d}$ can be written as

$$D_{pg}(\mathbf{s}, \mathbf{d}) = d(\mathbf{s}, \mathbf{d}) - H \cdot d_h, \qquad (2)$$

which shows that the propagation delay can be determined from the overall packet delay $d(\mathbf{s}, \mathbf{d})$, the number of hops along the measurement path H and the constant per-hop delay value $d_h = D_{tr} + D_{pc}$.

In the following subsection we show how the components of the d_h per-hop delay can be approximated.

A. Approximation of Per-Hop Delays

Usually the transmission delay can be neglected, since its contribution to the total delay is very small. For example, if we use small ($p = 56B$) packets over a $C = 1Gbps$ capacity link the contribution of the transmission delay is only $D_{tr} = p/C = 0.448\mu s$. For routers with higher physical capacities the transmission delay could be even smaller. Neglecting its value can lead to only $\approx 150m$ deviation in the approximation of the geographic distance.

The processing delay represents the time needed to process an incoming packet and to prepare it for further transmission on the next link. This delay depends on several software and hardware factors, like the network protocol, the computational power of the router and also the efficiency of the network interface cards. Besides these variable factors we treat the processing delay as a constant value for each router along the network path: $D_{pc}^i = D_{pc}$ for $i = 1 \dots H$.

The specific value of the processing delay can be determined by measuring router transmission times at very low traffic intensities. The authors of [9] performed thorough investigation of the processing delay of UDP and ICMP probes in different

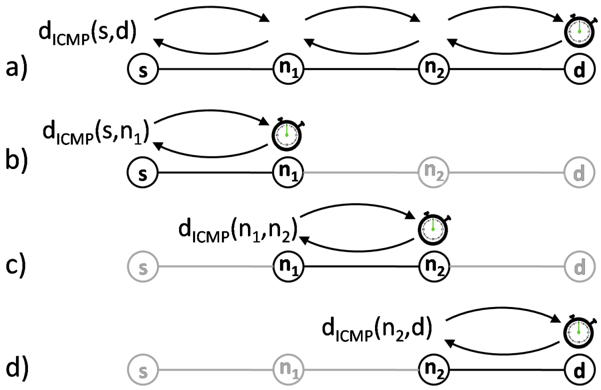

Fig. 1. Schematic view of the experiments performed in GÉANT2 network to determine the D_g ICMP Echo Reply packet generation time in case of a symmetric network path. a) shows the measurement of the overall round-trip delay of the path including the ICMP Echo Reply packet generation, while b), c) and d) represent the link-wise round-trip measurements.

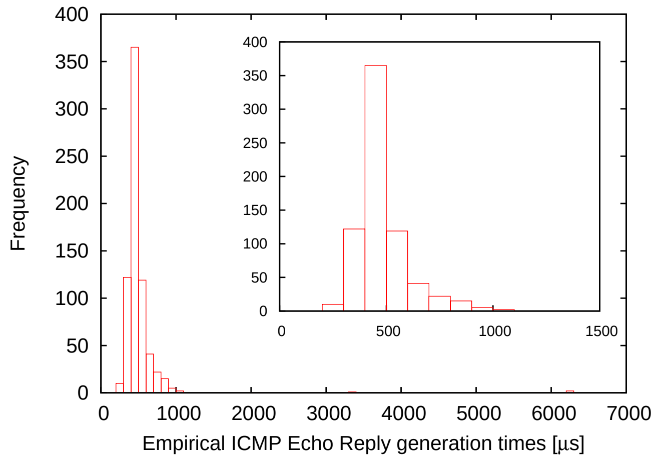

Fig. 2. Histogram of ICMP Echo Reply generation times based on RTT measurements. Each bin is $100\mu s$ wide.

kind of Cisco routers. They found that the processing delay is independent from the packet size, and the delay values for UDP and ICMP packets are almost the same: $D_{pc}^{\text{UDP}} \approx 97.9\mu s$ and $D_{pc}^{\text{ICMP}} \approx 101\mu s$. They also found some outliers due to some busy periods of the routers, which we ignore. In correspondence with these and other experimental results of [9], [11] we use the $D_{pc} \approx 100\mu s$ approximation for both UDP and ICMP packets. Based on the above observations in this paper we use $d_h = 100\mu s$ as a constant per-hop delay for all routers along the measurement path.

B. ICMP Echo Reply Generation Time

The delay estimation of various other geolocation techniques utilizes ICMP Echo (i.e. `ping`) measurements to approximate the overall delay between the target and landmark nodes. To apply the previously described path-latency model for a `ping` measurement, a minor but important extension is necessary. After the probe packet reaches the destination node, it is terminated and a newly generated ICMP Echo Reply packet is sent back. To model this process we need an additional term in the round-trip delay expression which describes the generation time of the Echo Reply packet:

$$d(\mathbf{s}, \mathbf{d}, \mathbf{s}) = d_{\text{fw}} + D_g + d_{\text{bw}}, \tag{3}$$

where D_g denotes the extra time elapsed due to generating the ICMP Echo Reply packet, while d_{fw} and d_{bw} represent the overall delay on the forward and backward directions respectively.

In the case of symmetric routing, the D_g packet generation time can be determined by subtracting the overall round-trip time from the sum of the link-wise round-trip times. In Figure 1 the schematic view of this measurement can be seen, where b), c) and d) represent the link-wise round-trip measurements, while a) represents the measurement of the overall round-trip delay of the path. The terms of (3) can be identified with the forward and backward arrows, while the D_g extra packet generation time is symbolized by a small clock in each row. Based on this scenario, we can estimate D_g with the following formula:

$$D_g = \frac{1}{H-1}\left(\sum_{i=1}^{H} d(\mathbf{n_{i-1}}, \mathbf{n_i}, \mathbf{n_{i-1}}) - d(\mathbf{s}, \mathbf{d}, \mathbf{s})\right). \tag{4}$$

Here we assume that the value of the D_g packet generation time is the same for all the routers along the path.

To determine the specific value of D_g we performed several experiments with the `GÉANT2` Looking Glass service [2]. Based on the `GÉANT2` topological information we defined a large number of symmetric network paths between the core routers, where all the routers belonging to these paths are accessible via the Looking Glass interface. By performing `ping` measurements along these paths we were able to collect all the terms appearing in (4) that are needed to estimate the average D_g value for the backbone routers. The histogram of the inferred D_g packet generation values are shown in Figure 2. To avoid wrong conclusions we take the minimal $D_g = 300\mu s$ value in our model. This result is in accordance with the literature [12], [13].

IV. Distance Approximation

The conversion between propagation delay and geographic distance is a key point in active geolocation techniques. To determine the relation between them, we need to determine an effective velocity considering the physical properties of all the links along the path and some kind of effective link curvature as well, since the network cables are not running straight from the source to their destination, due to practical reasons. To describe the effects of these properties we introduce a new parameter r, called *geographic signal propagation rate*, which is a conversion rate between the measured propagation delay and the real geographic distance in c units, where c denotes the speed of light in vacuum.

To determine the numerical value of r, we have collected a wide range of experimental results in the `GÉANT2` research network, using its Looking Glass service. From the known router positions we were able to determine their real geographic distances, while the latency values were also directly measured between them. Based on these data we approximated the r conversion rate according to the path-latency model.

The empirical minimum, average and maximum r values are 0.08, 0.27 and 0.47 respectively. These observations are in accordance with the measurement results in [7].

The approximated distance (s^*) should be an upper limit for the real distance (s), otherwise the evaluation might lead to an inconsistent equation system. Figure 3 shows the estimated and the real geographical distances between GÉANT-neighbors. It can be seen that the usage of the minimum and average ratios can lead to significant distance underestimation. On the other hand, by using the maximum velocity the probability of underestimation is small enough to avoid inconsistency in the evaluation. However, in this case the method usually overestimates the geographical distance, which of course decreases the accuracy of the geolocation estimation. As a conclusion of the above reasoning, we use the $r = 0.47$ value for the signal propagation in the network.

V. Solving the Geolocation Problem

We can handle the geolocation problem as a graph optimization task. The coordinates of the unknown routers represent the variables in the optimization problem. The goal is to determine the values of these variables according to the collected delay constraints. This non-convex optimization problem is well-known in the area of sensor networks. There are well documented techniques [17] that can be easily applied to solve this kind of equation systems. In this study a modified gradient method with adaptive step size was used to determine router locations by minimizing the overall tension in the system. More details about our approach can be found in [19].

In the following we overview the different type of measurements that can be used to define geographic constraints. In the optimization process geographic constraints provide information to mark out areas in the world map in which the target nodes are located with high probability. These constraints are obtained via latency and topology measurements from the landmarks. In this paper we limit ourselves to using latency measurements in constraint definitions, and do not apply any passive methods.

A. Round-trip Time Based Method

The `ping` tool is widely used in network measurements due to its simplicity and because it does not depend on having control over the target node. Although its inaccuracy is well known, the measured round-trip delays can give a constraint which defines an upper limit for the geographical distance between the landmark and the target node.

We have seen before that the round-trip time contains not only the delays on the forward and on the backward direction along a network path, but also the generation time of ICMP Echo Reply packet. Taking this into account, the $D_{pg}(\mathbf{s},\mathbf{d},\mathbf{s})$ round-trip propagation delay is written as $D_{pg}(\mathbf{s},\mathbf{d},\mathbf{s}) = d(\mathbf{s},\mathbf{d},\mathbf{s}) - (H_{\text{fw}} + H_{\text{bw}}) \cdot d_h - D_g$, where we assume equal processing and transmission delays, and negligible queuing delays at each hop. Based on the principle described in Section IV and the above expression we can limit the geographical distance between the source and destination nodes:

$$s(\mathbf{s},\mathbf{d}) \leq \frac{1}{2} \cdot c \cdot r \cdot (d(\mathbf{s},\mathbf{d},\mathbf{s}) - (H_{\text{fw}} + H_{\text{bw}}) \cdot d_h - D_g). \quad (5)$$

When the path is symmetric, its propagation delay is the same for both directions. In this case we can take the half of the round-trip time to approximate the one-way delay. It can be seen that in case of asymmetric paths, the real geographical distance could be even less than the above s^* limit.

B. Per-link Delay Estimation

Assuming that the network topology is known, we introduce a method to estimate per-link latencies, which then lead to the approximation of per-link distances. These information can improve the accuracy of the location estimation, since they give additional constraints to the geolocation. For consecutive $\mathbf{n_{i-1}}$ and $\mathbf{n_i}$ nodes on the network path between the $\mathbf{s}$ source and $\mathbf{d}$ destination, if there exists a directed route to $\mathbf{s}$ starting with the link $(\mathbf{n_i}, \mathbf{n_{i-1}})$, the link-wise distance can be defined as the difference of their distance from the common source node. Using this symmetric routing assumption the link-wise distance can be approximated as follows:

$$s(\mathbf{n_{i-1}},\mathbf{n_i}) = \frac{1}{2} \cdot c \cdot r \cdot (d(\mathbf{s},\mathbf{n_i},\mathbf{s}) - d(\mathbf{s},\mathbf{n_{i-1}},\mathbf{s}) - 2 \cdot d_h. \quad (6)$$

C. One-way Delay as Geographic Constraint

If we can measure precise one-way delays between all the landmark nodes and the paths between them are also available, then the one-way delays provide the value of $d(\mathbf{s},\mathbf{d})$ in (1). Using (2) we can similarly approximate the geographical distance along the full path as

$$\sum_{i=1}^{H-1} s(\mathbf{n_i},\mathbf{n_{i+1}}) \leq s^* = c \cdot r \cdot (d(\mathbf{s},\mathbf{d}) - H \cdot d_h). \quad (7)$$

This equation gives constraints for the coordinate variables of the $\mathbf{n}_i$ $(i = 1 \ldots H-1)$ nodes.

VI. Data Collection

In our geolocation system the data collection and the evaluation are separated into two independent phases. As a first step we collect delay data from round-trip and one-way delay experiments, while topological information are gathered by means of `traceroute` measurements. When all the data are available, we build up constraints and solve the given equation system as a global optimization problem.

Both the delay and topological data were collected in the ETOMIC system using its nodes as landmarks [1]. The ETOMIC infrastructure contains 18 GPS synchronized active probing nodes deployed across Europe, all of them equipped with high-precision DAG cards. All the collected measurement data are stored in the ETOMIC's Network Measurement Virtual Observatory [14].

We measured both round-trip delays to every target node and one-way delays between landmark pairs. In our data

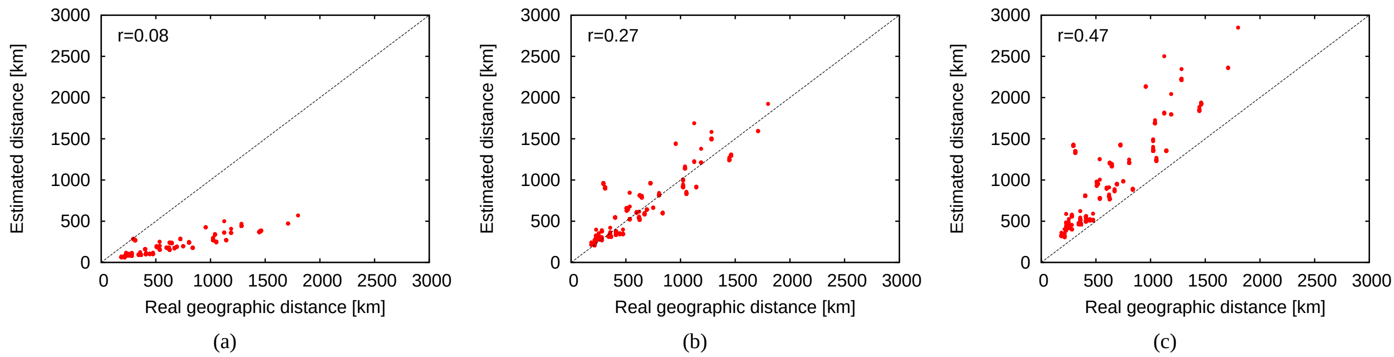

Fig. 3. The effect of using different signal propagation velocities in distance estimations. Figure a) shows the effect of using the minimum of the observed velocity values, which leads to distance underestimation. Figure b) represents the application of the average velocity value. In this case both under and overestimations occur. In Figure c) we use the maximum of the measured velocities, which decreases the possibility of distance underestimations.

collection a single round-trip delay measurement session contained 25 ICMP probes with 56 bytes packet size and the sessions were repeated 5 times in time-dispersed way. To measure one-way delays between ETOMIC nodes we used UDP packets with the same, 56 bytes packet size. To decrease the effect of the D_q queuing components in (2), every one-way delay measurement session contained more than 100 time-dispersed UDP probes. We determine the minimal round-trip and minimal one-way delay values. We assume that the effect of queuing delays can be neglected in this way.

Besides collecting delay values we ran a large number of `traceroute` experiments between each ETOMIC node pairs. Using these inter-ETOMIC paths we can define a directed graph that can contain nodes (i.e. IP addresses) that physically belong to the same router. If we cluster these interfaces into a single entity, we can decrease the number of unknowns in the evaluation method, and parallelly increase the precision and stability of the geolocation optimization.

A recent, reliable technique, the `Mercator` tool [16] was used to cluster the router interfaces. We applied `Mercator` on a large interface-set of IP addresses that contained 1192 elements, from which `Mercator` created 160 different clusters containing 584 interfaces. The remaining interfaces are also handled as clusters with a single interface. In this way we were able to identify 768 clustered nodes.

VII. Performance Analysis

Next we present the performance analysis of the evaluation, focusing on the role that different constraints played in the geolocation process. In our study, five different scenarios are investigated. First, we analyze a simple case, called *Geo-R*, where the overall delays are used as propagation delays and only round-trip time constrains are considered. Next, we also take into account our path-latency model to determine propagation delays (*Geo-Rh*). Next also the link-latency constraints are used (*Geo-RhL*). In the fourth scenario we use both round-trip and one-way delay constraints (*Geo-RhO*), and in the last setting all the introduced constraints are applied (Geo-RhOL).

By means of `ETOMIC` experiments we collected two reference node sets that contain backbone routers with known

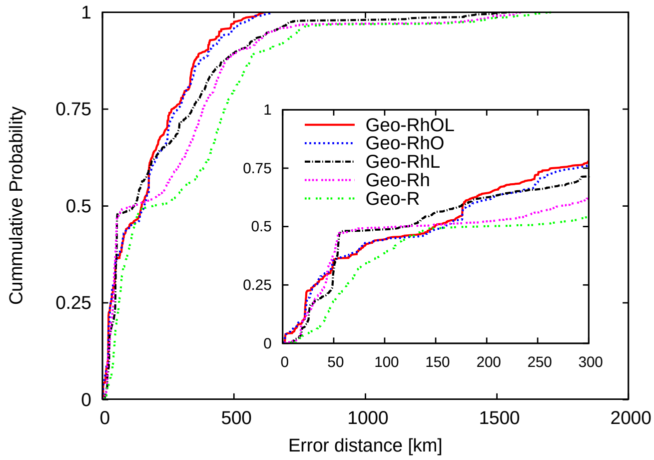

Fig. 4. Estimation errors of different scenarios for `Ref-1` reference data.

geographic positions (`Ref-1` and `Ref-2`). Locating a target node that is nearby a landmark, for example when they are in the same city, yields small estimation errors due to small measured delay values. To avoid misleading conclusions we selected nodes that are far from the landmarks. We performed several experiments to investigate the accuracy provided by our geolocation scenarios. Although the evaluation technique gives location estimates for all the nodes in the paths between the landmarks, the estimation errors are calculated only for the reference sets.

The `Ref-1` dataset contains 41 different interfaces, including `GÉANT2` routers and several other ones. We define `Ref-2` to increase the reliability of the applied methods. This is a subset of `Ref-1` with 20 elements, where all the nodes are in the convex hull spanned by the `ETOMIC` landmarks. The presented approach is slightly different from the usual geolocation techniques, where any IP addresses can be localized. Although our methods can provide more accurate location estimation for nodes that belong to the topology spanned by the landmarks. Hence, the direct comparison of our results to the prior works is not feasible.

TABLE II
ACCURACY WITH DIFFERENT CONSTRAINTS [KM]

Settings	REF-1			REF-2		
	Mean error	Max. error	StdDev	Mean error	Max. error	StdDev
Geo-R	304	1708	308	305	878	236
Geo-Rh	246	1602	288	251	699	205
Geo-RhL	213	1554	249	281	751	241
Geo-RhO	177	645	157	156	313	104
Geo-RhOL	169	609	149	149	312	104

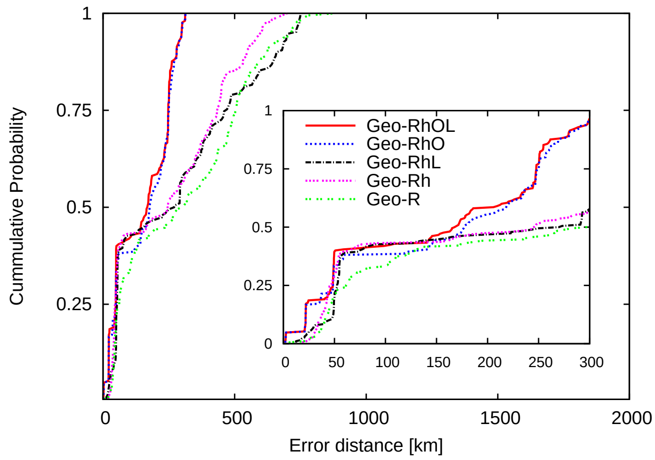

Fig. 5. Estimation errors of different scenarios for `Ref-2` reference data.

In Figure 4 and 5 we plotted the CDF curves of the location estimation errors for the two reference datasets. Both figures present all the five measurement scenarios. The main parameters of the observed error distributions can be seen in Table II for the reference sets.

By comparing `Geo-R` and `Geo-Rh` scenarios, one can observe that the median and mean errors are decreased by using the path-latency model, while on the maximum error the model has only a slight influence. In case of taking into account one-way delay constraints also the maximum error can be reduced, as it is shown in the table for `Geo-RhO` and `Geo-RhOL` scenarios. It is evident that the round-trip time based geolocation is inaccurate, since the area of possible locations could be wide due to the distance overestimation effect of inaccurate delay measurements. Using one-way delay constraints the range of possible locations of target nodes can be reduced significantly. In case of both reference datasets the observed estimation errors were much smaller than in the previous scenarios.

VIII. CONCLUSION

In this paper we investigated a model based approach of geolocation to demonstrate how an accurate approximation of the propagation delay can improve the accuracy of distance estimation. In contrast to the prior works, our path-latency model enables the separation of the propagation and per-hop delays in the overall packet latency. Besides the model based approximation of propagation delays, high-precision one-way delay measurements are used to define novel geographic constraints. This type of constraint yields additional information into the geolocation process by limiting the overall physical length of a given measurement path. This paper demonstrate that both the detailed path-latency model and the novel one-way delay constraints can significantly increase the accuracy of location estimates. The investigated techniques are tested and validated in a wide range of experiments performed in the `ETOMIC` measurement infrastructure and in the `GÉANT2` research network. In the future we will able to extend the number of landmark nodes and routers used for reference node set with the precise active measurement infrastructure of the OneLab2 project [18]. The introduced method can be included in existing geolocation frameworks to improve their accuracy.

ACKNOWLEDGEMENTS

The authors thank the partial support of the National Office for Research and Technology (NAP 2005/ KCKHA005), the EU ICT MOMENT Collaborative Project (Grant Agreement No.215225) and the EU ICT OneLab2 Integrated Project (Grant agreement No.224263).

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