The inter-domain hierarchy in measured and randomly generated AS-level topologies

Joanna Tomasik and Marc-Antoine Weisser
SUPELEC Systems Sciences
Computer Science Department
91192 Gif sur Yvette, France
{Joanna.Tomasik, Marc-Antoine.Weisser}@supelec.fr

Abstract—Independent operator networks are called either Autonomous Systems (AS) or domains. Numerous studies based on complex measurement platforms have been carried out for over ten years now in order to discover the Internet topology on domain level.

The routing realized by Border Gateway Protocol (BGP) is strongly influenced by commercial relationships which exist between domains, because domain operators do not want to make public the routes they know, as announcing certain routes would deprive them of a possible financial benefit. Consequently, routes available in BGP tables are valley-free and they are “spanned” on the inter-domain hierarchy. This property of BGP routes has an impact on the performance of protocols which are proposed to assure the QoS.

We examined the existing Internet topologies gathered on the domain level over the six year period in the context of their hierarchy. We used aSHIIP, our random hierarchical topology generator, to induct the hierarchy into the collected topologies. We proposed new methods for detecting the core of a network. Thanks to this analysis we have been able to put forward solid inter-domain hierarchy induction methods which are implemented in our publicly available tool.

Index terms: inter-domain hierarchy, valley-free route, random topology generation

I. INTRODUCTION

The goal of our work is to determine models of random topology generation which assure the adequate graph properties together with the most realistic hierarchy induced by the types of commercial relationships which exist between domains. The choice of these models is validated against the Internet measurements. In the rest of this paper we suppose that the term "domain" and the term "AS" are synonymous.

Inter-domain routing is ensured by Border Gateway Protocol (BGP) [1] which preserves each domain’s independence and announces routes arbitrarily chosen by the domains. The pioneer work of Gao [2] gave prominence to the existence of a hierarchy between Internet domains. This hierarchy is a result of commercial relationships established by contracts signed by domains’ owners. An important consequence of this hierarchy is that BGP routes have a particular shape, valley-free which will be explained in Section II.

In our studies concerning the Quality of Service (QoS) of the Internet on the domain level, we efficiently exploited this hierarchy. The idea is that a domain which is aware of heavily congested domains can choose a bypass instead of a route exhibiting possible problems of QoS satisfaction [3], [4]. In order to validate our heuristic algorithms, we needed a random network topology generator which included the inter-domain hierarchy. As such a generator did not exist, we wrote one [5]. This was the first version of our SHIIP (Supélec Hierarchy Inter-domain Inferring Program). Our initial generator used BRITE [6] to generate a random flat topology. Our method then transformed the flat topology into a hierarchical one.

Predicting the interest of the performance evaluation community in the modeling of inter-domain networks with the hierarchy, we decided to work on the generator in order to make it independent of BRITE and to improve the hierarchy inducting algorithm. The new SHIIP version, aSHIIP (“a” standing for “autonomous”) successfully deals with the real Internet topology. aSHIIP, announced briefly in [7] and discussed in detail in [8], is publicly available on a free license at http://wwwdi.supelec.fr/software/ashiip/.

Indeed, exploiting the Internet hierarchy gives researchers the idea to take advantage of this property when studying certain problems. The authors of [9] used SHIIP to evaluate resource allocation mechanisms in the inter-domain network within the context of operators’ alliances. In [10] SHIIP served in the performance analysis of handovers in the inter-domain context. aSHIIP is used by the partners of the European project ETICS [11] whose scope contains demonstrations of the effectiveness of new business models which call for random Internet-like topologies with the commercial hierarchy.

The reason for this study is developing aSHIIP by finding more appropriate methods of core detection and giving suggestions concerning the modeling of the inter-domain hierarchy. The validation of our propositions is based on the analysis of data measured over six years.

We start the next section by describing the principal platforms dedicated to measurements of the AS-level Internet. Later on that section discusses the AS-level topology as well as its hierarchy. Section III presents models used to generate flat topologies by aSHIIP and our methods of hierarchy induction. In Section IV we describe our contribution consisting in modifying the core identification procedure. In Section V we present the results of the hierarchy induction in the topologies gathered from measurements over time and in random ones using different core induction procedures. Finally, we give the conclusions and outline our future work.

The Autonomous Systems (AS) model is the most realistic model to capture the actual Internet topology. AS’s owners are independent so their routing is not influenced by external factors. Autonomous networks are called either Autonomous Systems (AS) or domains. Numerous studies based on complex measurement platforms have been carried out for over ten years now in order to discover the Internet topology on domain level.

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II. INTERNET TOPOLOGY ON INTER-DOMAIN LEVEL

There have been several attempts to measure the Internet graph on AS-level. We can distinguish two methodologies of the topology discovery on this level [8]. The first one is passive and consists in analyzing BGP route announcements from different vantage points (RouteViews [12], RIS of RIPE NCC [13]). The second relies on the sending of probes (Archipelago [14], iPlane [15], RocketFuel [16]). The use of community software agents to actively retrieve the Internet structure is proposed in [17], which presents the project DIMES.

The measurement methodology of the Internet on the domain level has to overcome several important problems. We count among them 1) the choice of vantage points and the number of these points required [18], [19], 2) the impact of a bias caused by exploration of trace-routes [20], [21], 3) the difficulties caused by the fact that IP-to-AS mapping extracted from BGP routing tables is not sufficient to determine the AS-level forwarding paths [22], [23], and 4) the existence of hidden links whose discovery potentially needs a long monitoring time and invisible links which cannot be detected by monitors [24].

Despite the difficulties mentioned above, the common agreement concerns a domain degree distribution which follows a power law [25] in spite of some reservations being expressed, for instance, in [26]. A power distribution of domain degree in the Internet is an assumption in our study.

The existence of the Internet hierarchy imposed by commercial relationships between domains was announced in [2]. These relationships depend on commercial contracts signed by domain operators and can be defined as follows:

- **P2C, provider-to-customer**, assigned to a link between a provider domain which is buying a connectivity service from a customer domain,
- **P2P, peer-to-peer**, assigned to a link between two domains which share connectivity, and
- **S2S, sibling-to-sibling**, assigned to a link between two domains which are owned by the same operator.

The **P2C** and **P2P** relationships introduce a hierarchy imposing layers in the inter-domain network [27], [18]. As **S2S** links are rare (approximately one percent of all links [28], [29]) their influence on the hierarchy is negligible. Some authors [30], [31] claim, however, that an erroneous inference of **S2S** relationships can have a further disastrous impact on the induction of **P2C** and **P2P** links. The core, **Tier-1**, is at the top. It is a set of domains which are linked by **P2P**. The domains of the core are not customers of any domain. Each domain of the core is connected to all (or almost all) other domains of the core. Usually, the domains in the layer **Tier-i** are providers of domains in the layer **Tier-j** with \( j > i \). The domains in **Tier-j** are customers of domains in **Tier-i**, \( i < j \). The domains in **Tier-i** and in **Tier-j** are linked together with **P2C**. Domains in the same layer can be linked together with **P2P** or **P2C**. The average percentage of domains in each layer increases strictly (starting from **Tier-1**). The average degree of a domain in a layer decreases strictly (starting from **Tier-1**).

The inter-domain hierarchy has an impact on the current inter-domain routing because the BGP operational principle takes into account commercial agreements and financial compensation:

- a customer domain announces to its customers, peers, and providers the routes which it can establish,
- a provider domain announces its routes to its customers only,
- a peer announces available routes via its peers to its own customers only.

This principle implies that routes announced in the inter-domain network are valley-free. They are made of uphill and downhill components connected by, at most, one **P2P** link. An uphill component is a list of consecutive links labeled **C2P** which is dual to **P2C**. A downhill component is a list of consecutive links labeled **P2C**.

III. HIERARCHICAL TOPOLOGIES WITH aSHIIP

aSHIIP uses models of flat topology generation and inducts the hierarchy into it afterward. To begin we present the commonly accepted models to random topology generation.

One of the earliest generators of random topologies is the Waxman generator [32] which is based on studies carried out by Erdös and Rényi [33], [34] on theoretical graphs prior to the network era. The other existing generators of random topologies can be divided into two categories. The first one contains generators whose operating mode is based on the degree approach. This approach allows one to reproduce local properties of the network (connectivity, clustering). The generators such as Inet [35], models of Aiello et al. [36], Barabási and Albert (BA, also referred to as Preferential Attachment, PA, model) [37] and its extended version (BA2) [38], the general linear preference one (GLP) [39] are all members of this first group. A new member of this family is the multiclass preferential attachment (MPA) model which has been recently proposed by the members of the Caida association [40]. It is based on the BA model and dedicated to the AS-level topology.

The second category of generators is based on a topology structure which allows them to represent global network properties such as a hierarchical structure (Tiers [41], Transit-Stub [42]). These two generators produce topologies with a predefined layer number and the node degree does not follow a power law.

As already pointed out in the previous section, numerous studies have shown a close relationship between the distribution of node degree in networks and a power law. A power law concerning node degrees is also valid on the inter-domain level, as observed in [25]. The further study [19] confirmed this observation for the Internet despite the latter’s intensive development during the ten years separating these two papers. The models cited above in the degree approach context produce random graphs which exhibit a degree distribution following a power law.

aSHIIP starts by generating a random flat topology. It offers the following generation models, among those discussed above: Waxman [32], Aiello et al. [36], Barabási and Albert,
BA and BA2 [37], [38], and GLP [39]. All these models but one (Waxman) ensure a power law distribution of the node degree. aSHIIP offers the Waxman model because of its popularity. aSHIIP systematically checks the connectivity of generated topologies. In the case of a topology which is not connected, its greatest component is returned.

Next, the hierarchy is inducted in a flat topology according to three criteria (clique, size, degree) we distinguished in [5]

- the network core (Tier-1) is a complete graph,
- the average size of Tier-i is strictly less than the one of Tier-j when i < j,
- the average number of domains connected to a domain in a layer decreases strictly starting from the core.

We have recently revised the first one, which was originally applied in SHIIP [5], which looked for a natural clique composed of the nodes with the largest degree according to the statements about core domains’ degrees made in [18], [43] (an idea similar to the one in the Jellyfish model [44]). In aSHIIP we allowed the core to be an “almost complete graph” because we observed that the core which was set up as a clique might be unreasonably small compared to an artificial size in this paper. We propose other core inducing methods in order to obtain the reliable commercial hierarchy. We discuss the core inducing procedures in detail in the next section.

IV. NEW METHODS OF CORE DETECTION

In our work to improve the veracity of hierarchical topologies generated by aSHIIP [7], [8] we focused on the best fit of artificial stratified graphs to the snapshot of 33507 ASes done by Caida on Jan 20, 2010 [45] whose average node degree (ADg) is 4.4 and maximal node degree (maxADg) is 2502. From a theoretical maximum power law property \( k_{\text{max}}^{\text{PL}} = n \frac{1}{\alpha} \) [46] we obtain the coefficient \( \gamma = 2.331 \).

The induction of the hierarchy into this topology with aSHIIP “slices” the graph into six layers whose node percentages and ADg are given in the table below. There are 13 percent of links labeled P2P.

<table>
<thead>
<tr>
<th>Tier-1</th>
<th>Tier-2</th>
<th>Tier-3</th>
<th>Tier-4</th>
<th>Tier-5</th>
<th>Tier-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>node %</td>
<td>0.02 (23 ASes)</td>
<td>10.38</td>
<td>43.45</td>
<td>42.45</td>
<td>3.68</td>
</tr>
<tr>
<td>ADg</td>
<td>950.53</td>
<td>44.56</td>
<td>4.14</td>
<td>2.11</td>
<td>1.95</td>
</tr>
</tbody>
</table>

In [8] we stated a hypothesis that Tier-3 in artificial topologies is narrower than the one in the Caida measured topology because the real node degree distribution does not fall as quickly for small degree value as the power distribution does.

The results which we presented in [7], [8] convinced us to pursue the development of the hierarchy induction. We have given ourselves two axes to study: 1) to propose other methods to find the core, which accept more nodes than the one implemented in aSHIIP which may be seen as too restrictive when dealing with random topologies, and 2) to validate the inducted hierarchy against historical measurements to assure a proper scalability of our models in the future.

We continue to work on topologies from Caida. We decided not to confront our artificial topologies against the other available measurements yet in order not to introduce a supplementary degree of freedom in the model parameterization.

The three methods we propose to identify the Tier-1 are based on the local approach. We look for a very dense subgraph which is “almost” a clique and we expect to obtain the core composed of almost 20 fully-connected domains which the authors of [31] found the best for further interference of the type of relationships, also showing that the global approach (k-Core [47]) leads to the unreasonably big core. Our goal consists in finding the core of the size in accordance to results obtained from measurements and whose localization in a network gives a correct identification of the lower Tiers.

“clique” with two missing edges on node level, 2N-core:

The core is recursively formed out of nodes whose degrees are the highest. An added node can be short of up to two edges to constitute a complete graph in the final core. On each recursive step a decision of accepting/rejecting a current node is taken therefore the number of operations to be potentially executed is in \( O(2^n) \) where \( n \) is a number of nodes to be considered as possible core elements. We have to limit arbitrarily \( n \) to 40 for the numerical purposes. We observed, however, that in practice the computation takes a much shorter time, up to \( 2^{20} \) because the reject of a node which is not connected with more than two nodes of the final core stops the recursive procedure.

“clique” with three missing edges on node level, 3N-core:

This method is the same as the previous one but it allows a node to be short of up to three edges to the nodes of the final core. The number of nodes considered as potential nodes of the core is arbitrarily limited to 20.

These two methods, however, may potentially suffer from an influence of the node order established according to the node degree and produce an unacceptably small core. To overcome this possible weakness we propose below another method which varies the number of missing edges in function of the depth of its recursive execution.

“clique” with \( 2k \) missing edges on clique level, 2kC-core:

The core is composed of nodes whose degrees are the highest. On the \( k^{\text{th}} \) recursive step a \( k^\text{th} \) node is admitted under condition that at most \( 2k \) links are missing to make the final core complete. The nodes are added one by one until reaching
potentially 20 nodes. A node which would introduce more than $2k$ missing links stops the recursive procedure.

We do not continue to look for a “clique” with $3k$ missing edges as it would produce an insufficiently dense core.

V. CONFRONTATION OF HIERARCHY INDUCTED IN MEASURED AND GENERATED TOPOLOGIES

As we pointed out in Section II there are numerous methodologies to discover the Internet topology. For the reasons explained in the previous section we focus on the topologies gathered by Caida [45] over six years. We introduce the interdomain hierarchy into these measures topologies according to the methods offered by aSHIIP. We do the sale with randomly generated topologies which preserve $\text{aDg}$ or $\gamma$. The topology stratification is made in both the cases with the different algorithms of core detection (see Section IV).

We begin by detecting the hierarchical layers in the Caida measured topologies using the $2\text{eN-core}$ method. The core size is between 11 and 15 ASes and the $P2P$ percentage varies between 9 and 13. The results in Fig. 1 indicate$^1$ that $\text{Tier-3}$ is always significant. An undesired phenomenon can, however, be observed when looking at the percentage of nodes on the second layer which oscillates between 7.36 and 15.62. We can guess that $2\text{eN-core}$ has difficulty detecting the core border. This hypothesis finds its confirmation in Fig. 2 in which we see that $2\text{eN-core}$ may attribute nodes of high degree to $\text{Tier-2}$ rather than to the core. To overcome this “hesitation” seen on the border between $\text{Tier-1}$ and $\text{Tier-2}$ we apply core induction according to the methods $3\text{eN-core}$ and $2\text{kC-core}$. In Fig. 3 we notice that $2\text{kC-core}$ chooses the nodes better to construct the core because neither the core size nor its $\text{aDg}$ suffers from violent variations and the $\text{aDg}$ exhibits almost regular growth. However, one sharp exception may be observed for all the three methods for the topology of 31297 ASes gathered on Apr 29, 2009. One may expect that the measurements taken on this day were incomplete. Indeed, in Fig. 4 we see a clear fall of both the $\text{aDg}$ and $\text{maxDg}$ and a rise of $\gamma$ of the topology measured on this date.

The core detection method for which we opt is $2\text{kC-core}$. The node percentages in layers and $\text{aDgs}$ are depicted in Figs. 5 (see note 1) and 6. The core size varies between 16 and 19, the $P2P$ percentage is between 8 and 12.

Resting on the Caida historical data (Fig. 4) we notice that their values exhibit a global increasing tendency. The model

$^1$The node percentages do not add up to 100% because the diagram does not take into account either the core or the sixth layer whose size is comparable with the core size or the peripheral seventh layer which occasionally exists and contains up to about ten domains.

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### Fig. 1. Node distribution in layers in the measured topologies, $2\text{eN-core}$

<table>
<thead>
<tr>
<th>Layer</th>
<th>Size</th>
<th>Average Degree</th>
<th>Maximum Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>2.3</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>2.4</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>2.6</td>
<td>5.0</td>
</tr>
</tbody>
</table>

### Fig. 2. $\text{aDg}$ on layers in the measured topologies, $2\text{eN-core}$

<table>
<thead>
<tr>
<th>Layer</th>
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</tr>
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</tr>
<tr>
<td>5</td>
<td>12</td>
<td>2.6</td>
<td>5.0</td>
</tr>
</tbody>
</table>

### Fig. 3. Core size and its $\text{aDg}$ detected by the three proposed methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Core Size</th>
<th>Average Degree</th>
<th>Maximum Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\text{eN-core}$</td>
<td>11</td>
<td>2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>$2\text{kC-core}$</td>
<td>15</td>
<td>2.3</td>
<td>3.5</td>
</tr>
<tr>
<td>$3\text{eN-core}$</td>
<td>13</td>
<td>2.4</td>
<td>4.0</td>
</tr>
</tbody>
</table>

### Fig. 4. $\text{maxDg}$, $\text{aDg}$ and $\gamma$ in Caida measured topologies

<table>
<thead>
<tr>
<th>Date</th>
<th>$\text{maxDg}$</th>
<th>$\text{aDg}$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-01</td>
<td>1000</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>2005-01</td>
<td>1500</td>
<td>2000</td>
<td>1</td>
</tr>
<tr>
<td>2006-01</td>
<td>2500</td>
<td>3000</td>
<td>1</td>
</tr>
<tr>
<td>2007-01</td>
<td>3000</td>
<td>3500</td>
<td>1</td>
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<tr>
<td>2008-01</td>
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<td>2009-01</td>
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<td>1</td>
</tr>
<tr>
<td>2010-01</td>
<td>4500</td>
<td>5000</td>
<td>1</td>
</tr>
</tbody>
</table>
GLP with $m_0 = 10$, $m = 1$, $p = 0.548$ and $\beta = 0.80$ preserves the $\text{aDg}$ of 4.4 but $\gamma$ is of 2.54 (see also Section IV). We call it the GLP-\text{average} model. The GLP model which preserves $\gamma$ of 2.33, called GLP-\text{$\gamma$}, is parameterized as follows: $m_0 = 15$, $m = 1$, $p = 0.18$ and $\beta = 0.95$. In this case the $\text{aDg}$ falls to 2.34. These parameters are different than those given in [39] and applied notably in [48] for which the graph of size 33507 has the $\text{aDg}$ of 6.54 and the $\text{maxDg}$ of 708 which gives the $\gamma$ approximation 2.588. We can notice that the parameters computed eight years earlier give for the current Internet size a graph whose degree distribution varies considerably less and the $\text{maxDg}$ is relatively small.

The average stratifications for both GLP models realized for series of 1000 topologies are presented in Figs. 7 and 8 (see note 1). The mean core sizes of topologies generated with the GLP-\text{average} and GLP-\text{$\gamma$} models are 11.84 and 8.18, respectively. The P2P ratios are 17 and 5, respectively. The GLP-\text{average} graphs offer the realistic core size and P2P ratio. Tier-2 and Tier-3, however, are narrower than in the Caida topologies. This fact straightens our hypothesis (Section IV) that the node degree distribution in GLP topologies decays more violently than in the measured ones. In GLP-\text{$\gamma$} topologies the layer percentages are similar to those in the Caida data but the weaker connectivity of graphs leads to the small core and the insufficient P2P percentage. Thus we opt for the GLP-\text{average} model.

VI. CONCLUSIONS AND FURTHER WORK

The demand of designers of control mechanisms and of inventors of business models for the AS-level Internet justified our work on a random network generator adapted to deal with hierarchical Internet-like topologies on domain level. We propose heuristic algorithms which: look for the Internet core, divide the domains into layers, and correct any errors of the preceding division algorithms. We insist on the induction of the core which corresponds the best possible to the recent findings about its nature because its choice determines the further graph stratification. In our opinion our new method 2kC-core consisting in selecting a dense graph of $k$ nodes which can miss at most $2k$ edges to be a clique gives realistic results.

We performed experiments on the Caida measurements over time in order to determine the best adapted generation model and its parameters. The exhaustive validation procedure which we realized allows us to consider our generator as a reliable modeling means of the AS-level Internet.

In the short term we would like to expand the list of...
generation models available in our generator by the recently proposed MPA [40] which is dedicated to AS-level topologies and Inet [35] whose static metrics are recommended by [48].

We see, however, an important axis of aSHIIP future evolution in the long term. In our opinion the generator should be enriched by some temporal parameters describing notably a transit time per domain, as this factor is crucial to estimate transmission delays in the context of QoS satisfaction. We realize that the introduction of this new feature means that we will have to overcome numerous difficulties in performing and interpreting Internet measurements.

Recent changes in the commercial strategies of many Internet companies have had a potential impact on the Internet hierarchy. In fact content providers now wish to build their own WAN infrastructures [49]. Such deployments aim to bring networks “closer” to customers. The phenomena accompanying the architectural changes are notably 1) a great degree of content domains [24], and 2) the bypassing of core domains on many paths [49]. If these trends establish themselves permanently on the Internet, its hierarchical structure will have to be revised. We argue that the analysis of transit time per domain might be a means to detect distortions of the Internet companies have had a potential impact on the Internet hierarchy from multiple vantage points, and Inet [35] whose static metrics are recommended by [48].

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Our generator aSHIIP (autonomous Supélec Inter-domain Inferring Program) is available on a free license at http://wwwdi.supelec.fr/software/ashiip/

REFERENCES