BGP Prefix Delegations: A Deep Dive

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ABSTRACT

Among the scalability limits in the Internet routing ecosystem are the BGP routing table size and the rate of updates. In this paper, we focus on the former. The BGP routing table size has been growing superlinearly in the past decades. Although the address space allocation was structured with aggregation in mind, this capability is impaired due in part to the need for traffic engineering. One major impairment are delegated prefixes.

Prefix delegations contribute 15% to the routing table size and they also involve 14% of the traffic. Moreover, they reflect the large complexity of BGP: Delegations are not only the results of providers delegating address space to their customers but also vice versa. Some delegations are due to load balancing and transitive business relationships, others due to operational practices within organizations.

We analyze BGP data as well as large-scale traceroute data to understand how delegations affect path selection. Although the need for delegations is apparent, our work highlights that the fragmentation of address space is going to continue and renders the routing table more and more unaggregatable.

1. INTRODUCTION

In the Internet, *autonomous systems* (AS) have two ways to obtain routable IPv4 addresses. They can request so-called *provider-independent* (PI) address space from their *regional internet registry* (RIR), however, IPv4 addresses are exhausted and new allocations are rare [17]. Another way to obtain IPv4 addresses is via provider ASes. Provider ASes sub-allocate so-called *provider-aggregatable* (PA) address space to their customers. This process is often referred to as *prefix delegation* [8, 20].

Considering the IPv4 address exhaustion and the aggregatability of PA address space, it is surprising that the number of prefixes in routing tables is still increasing. By now the global BGP routing table contains more than 600,000 IPv4 prefixes and has been growing at an annual rate of roughly 50k [3].

Aggregation of prefixes is considered crucial for reducing the routing table size as well as the rate of BGP updates. Operators rely on deaggregation and often tolerate the consequent bloat of the routing table to enable services such as multi-homing and realize traffic engineering [6, 8, 16]. We confirm that deaggregation is increasingly contributing to the growth of the routing table [8]. Indeed, today's heavy use of deaggregation—by some considered abuse—renders the routing table more and more un-aggregatable. At the same time it shows the lack of alternative means to satisfy the needs of today's Internet routing system.

A common explanation/observation for deaggregated prefixes leaking into the routing system is the delegation of PA prefixes to a multi-homed AS. Even though the PA prefix can be aggregated by the delegating provider it cannot be aggregated by other providers. Thus, the prefix adds to the routing table. Moreover, the aggregation by the delegating provider may lead to undesired routing.

In this paper we focus on such prefix delegations by mining ten years of publicly available BGP data. Using traffic data from one of the largest European *Internet exchange points* (IXP), we find that more than 14% of its traffic is originating from delegated prefixes while 5% of the traffic is addressed to them.

To better understand prefix delegations, we subclassify delegated prefixes into four categories based on the AS path of prefix announcements. We then use large-scale traceroute measurements to quantify the impact on the actual traffic flow. To our surprise, we find a variety of prefix delegations including from-customer-to-provider or delegations among ASes that have no apparent topological relation. More specifically, we find:

- Around 53% of all delegations concern PA prefixes from provider to customer.
- 10% of delegations are from customer to provider. These are in the fastest growing delegation class.
- 34% of the delegations are among ASes with no obvious business relationship. While there is no single reason for such delegations we highlight—using case

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studies—that they can be used for sophisticated traffic engineering.

Prefix delegations are more complex than commonly presumed. With regard to the routing table growth, this is bad news. Our findings highlight that the fragmentation of address space is going to continue and that it is not necessarily aligned with AS relationships.

2. BACKGROUND & RELATED WORK

AS-level Internet and BGP: The Internet consists of more than 50,000 interconnected *autonomous systems* (AS). An AS is a network which is operated as a single administrative entity. Usually, neighboring ASes have complex contractual agreements that govern their routing policies. Common agreements include: *provider/customer* and *peering*. Customers pay their provider for the traffic (volume) that they exchange and get access to Internet routes. In a peering relationship both ASes exchange their traffic and that of their customers on a settlement-free basis. In *sibling* relationships the routing policies are mixtures and the two involved ASes often belong to the same administrative entity. Although provider/customer and peering make up the majority of business relationships in the Internet, more complex relationships exist and become more common-place [10].

To exchange routing information ASes use the *Border Gateway Protocol* (BGP), the de-facto standard inter-AS routing protocol. With BGP ASes selectively originate and forward prefix announcements to neighboring ASes. BGP is a path vector protocol, i.e., whenever an announcement is forwarded each AS appends its own AS number to the *AS path* attribute. The AS path, i.e., a sequence of AS numbers, is used for loop detection and as distance metric. The AS that originates the announcement is the *origin AS*.

Since BGP configuration is error prone, e.g., [7], it is critical for operators to view the routes they announce. Thus, BGP collectors, e.g., RIPE RIS and RouteViews, have collected *BGP updates*, i.e., prefix announcements and withdrawals, over many years. Although the collectors do not cover the whole AS topology, e.g., [12, 18, 19], the data is used for many other studies as it is sufficient to infer the AS graph, e.g., [6, 8–10, 13, 14, 16].

Business relationship inference: Usually, ASes do not disclose their specific routing policies. As a consequence, business relationships have to be inferred. Most inference algorithms rely on the assumption that there is no economic incentive to forward traffic across two peering links or via a customer. This is captured by the valley free property, e.g., see [9]. An AS path is *valley free* if a provider-to-customer (p2c) or peer-to-peer (p2p) edge is not succeeded by a customer-to-provider (c2p) or peer-to-peer edge.

One approach, presented by Luckie et al. [14], relies on the assumption that (i) there is a clique of peering ASes at the top of the hierarchy, (ii) most customers enter a transit agreement to be globally reachable and (iii) cycles of p2c links should not exist to enable routing convergence. In the same work the authors present multiple methods to infer the customer cone of an AS; a set of ASes that can be reached by traversing p2c links only.

Related work: McDaniel et al. [15] use a delegation tree to study the feasibility of origin authentication. While studying the growth of the Internet, Sriraman et al. [21] use allocation data from RIRs and BGP prefixes to construct a delegation hierarchy. Motivated by the increasing routing table size, Cittadini et al. [8] analyze overlapping prefixes, by relying on BGP data. While their focus is on deaggregation, they infer a widespread use of AS path prepending and scoped advertisements. Similarly, Bu et al. and Meng et al. [6, 16] use overlapping prefixes and the AS path to infer load balancing and multi-homing and their impact on the routing table growth.

3. DATA SOURCES

In this work we use a variety of data sets. We first obtain and clean publicly available BGP data, in order to identify and classify delegated prefixes. Then we use several data sets from CAIDA to study the relationships among the involved ASes and how delegations affect the traffic flow.

BGP: We download BGP data from BGP collectors maintained by RouteViews [5] (*rviews*) and RIPE RIS [4] (*ripe*). Since BGP is a routing protocol and not a measurement tool the collected data suffers from misconfigurations, errors, etc. It contains artifacts such as unallocated AS numbers, unallocated prefixes and poisoned paths, e.g., AS paths with loops. We clean our data set by removing such announcements. We also remove announcements from beacon ASes or compatibility AS numbers. In addition, we remove prepended ASes in the AS paths. Contrary to other BGP studies, we keep all prefixes independent of the prefix length. We further clean the data set by removing announcements that are not suitable/compatible for the delegation classification, see Section 4. This includes those with an AS path length less than two, with AS sets, and with ambiguous information, e.g., prefixes with multiple origins. The latter affects around 1% of the overall prefixes before cleaning. Table 1 and Figure 1 summarize our data sets before and after cleaning. By merging the data from *ripe* and *rviews* the total number of prefixes increases only slightly. Adding the updates does not substantially increase the number of prefixes either. While data cleaning does remove some information it does not drastically reduce the number of prefixes in both data sets. For a longitudinal study we use routing table dump snapshots which contain the routing information base (RIB) from 2006 to 2016 every 6 months for one day (d_{hist}). To study prefix delegations in January 2016 in more detail we also include BGP updates (d_{2016}).

CAIDA: We augment our data with AS business relationships using the data from Luckie et al. [14] ($d_{business}$). It labels AS pairs as either p2c or p2p. Furthermore, we use the corresponding customer cone data set [14] (d_{cone}). We enhance the above data sets with complex AS relationships from Giotsas et al. [10] ($d_{complex}$) as well as with additional AS links in IXPs from Giotsas et al. [11] (d_{mlp}). We further use CAIDA's AS-to-organization data set which pro-

source	# prefixes RIB	# updates	total
ripe	635k (-4%)	590k (-3%)	644k (-5%)
rviews	667k (-4%)	597k (-2%)	668k (-4%)
both	686k (-6%)	610k (-4%)	696k (-7%)

Table 1: Overview of BGP data set d_{2016}. In parentheses relative decrease after cleaning.

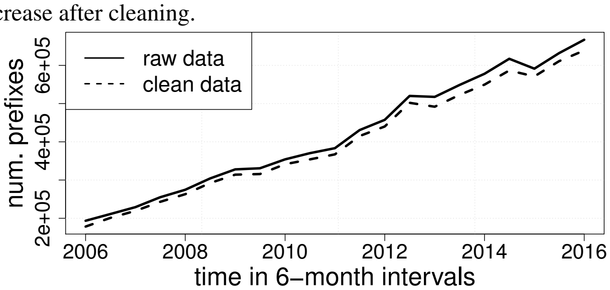


Figure 1: Overview of BGP data set d_{hist}.

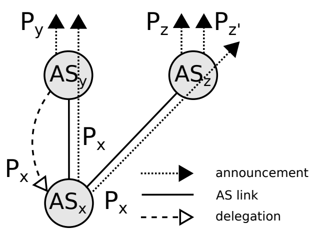


Figure 2: Multi-homing example

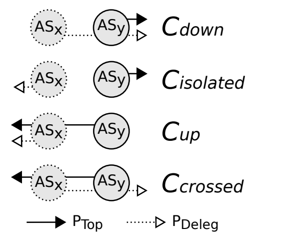


Figure 3: Delegation classification

vides unique organization identifiers mapped to AS numbers [2] (d_{org}). Finally, we use large-scale traceroute measurements taken by CAIDA's Archipelago infrastructure [1] (d_{trace}). We obtained these data sets from the same time period as d_{2016}.

4. PREFIX DELEGATIONS

In this section we describe how we identify and classify prefix delegations. Hereby, we use the following notation: For a prefix P_α, AS_α refers to the AS that originates the prefix. $Path(P_\alpha)$ refers to the set of paths that are recorded for the prefix.

Consider the example of a multi-homed environment where AS_x is a customer of AS_y and AS_z, see Figure 2. AS_z announces a *deaggregated* prefix. More specifically, $P_{z'}$ is deaggregated from P_z and both are announced by the same AS_z. AS_x announces a *delegated* prefix, namely P_x which is a subset of P_y. Thus, P_x is deaggregated from P_y and delegated to/announced by AS_x.

Prefix classification: To identify delegations we classify prefixes based on their overlapping properties and the origin AS. More specifically, we first check if any two prefixes are subsets of each other, i.e., $P_x \subset P_y$. If positive, we further check if they are announced by the same AS, i.e., $AS_x = AS_y$. Inspired by Cittadini et al. [8] we distinguish the following prefix classes:

$P_{lonely} : \nexists\ P$ where $P_{lonely} \subset P \vee P \subset P_{lonely}$
$P_{top} : \nexists\ P, \exists\ P'$ where $P_{top} \subset P \wedge P' \subset P_{top}$
$P_{deagg} : \exists!\ P_{top}$ where $P_{deagg} \subset P_{top} \wedge AS_{deagg} = AS_{top}$
$P_{deleg} : \exists!\ P_{top}$ where $P_{deleg} \subset P_{top} \wedge AS_{deleg} \neq AS_{top}$

In words, prefixes in P_{lonely} do not overlap with any other prefix. Prefixes in P_{top} are always the less specific of two overlapping prefixes. The more specific prefixes are either in P_{deagg} or P_{deleg}. If two prefixes P and P' overlap and P is in P_{top} then P' must be in P_{deagg} or P_{deleg}. It is in P_{deagg} if both prefixes are announced by the same AS. If the prefixes are announced by different ASes P' is in P_{deleg}. We refer to the AS that is originating P as AS_{top} and the AS that is originating P' either as AS_{deleg} or AS_{deagg}. Hereby, AS_{deagg} is the same as AS_{top}.

Delegation classification: After using the above method to identify delegations, we next subclassify them into four different classes. We analyze AS paths of each prefix in P_{deleg} and of the correspondent less specific prefix in P_{top}. Considering the example of AS_y delegating address space to AS_x, as shown in Fig. 2, we check for two properties in the respective AS paths: (i) AS_x announces the more specific prefix via AS_y and (ii) while AS_y announces the less specific one, the announcement does not pass through AS_x. Delegations with these properties are in C_{down}[1]. While this is the most intuitive, other combinations exist as well, see Figure 3. Note, this classification does not require the existence of an AS link between both ASes. We distinguish the following four delegation classes:

$C_{down} : AS_{top} \in Path(P_{deleg}) \wedge AS_{deleg} \notin Path(P_{top})$.
$C_{isolated} : AS_{top} \notin Path(P_{deleg}) \wedge AS_{deleg} \notin Path(P_{top})$.
$C_{up} : AS_{top} \notin Path(P_{deleg}) \wedge AS_{deleg} \in Path(P_{top})$.
$C_{crossed} : AS_{top} \in Path(P_{deleg}) \wedge AS_{deleg} \in Path(P_{top})$.

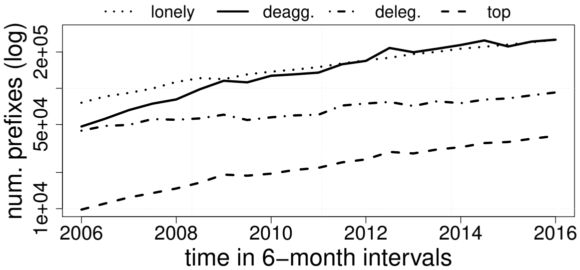
In effect, the class C_{up} is the opposite of C_{down}. In C_{up} the delegator announces the less specific prefix via the delegatee and the delegatee announces the more specific prefix but not via the delegator. $C_{isolated}$ and $C_{crossed}$ cover the two remaining cases. In $C_{isolated}$ both the delegator and the delegatee announce their prefix separately. In $C_{crossed}$ the delegator announces the less specific prefix via the delegatee and the delegatee announces the more specific prefix via the delegator.

5. DELEGATIONS ACROSS 10 YEARS

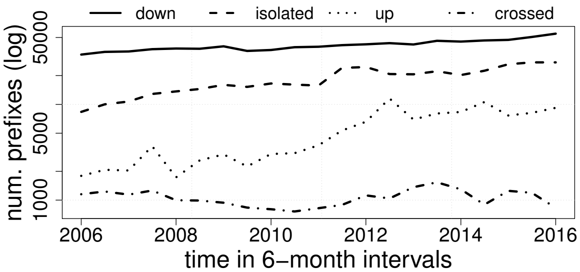
Using d_{hist}, Figure 4(a) shows how each class of prefixes: P_{top}, P_{lonely}, P_{deagg} and P_{deleg} evolved. All prefix classes have grown at almost constant rate over the past ten years. In 2006 the number of prefixes in P_{deagg} was about the same as those in P_{deleg}. In fact, Cittadini et al. [8] show that before 2006 P_{deleg} had an even bigger share of the routing table than P_{deagg}. The authors conjectured that the increased popularity of PI address space led to the changes in these classes. Today, P_{deagg} is the fastest growing class—by a factor of 5.3— and is among the largest classes since 2009. In January 2016 P_{deleg} make up 14.6% of the routing table size which corresponds to more than 93k prefixes, see Table 2.

Even though P_{deleg} is not growing as fast as some of the other classes, we consider *delegated prefixes* the most intriguing class as they reflect the large complexity of BGP;

[1]The notation C_{down} implies the delegation going *down* the AS level hierarchy, e.g., from provider to customer.



(a) Prefix classes over time.



(b) Delegation classes over time.

Figure 4: Longitudinal study, d_{hist}: Jan. 2006 to Jan 2016.

Prefix class	#Prefixes	%Prefixes	#ASes
P_{lonely}	252,917	39.2%	38,971
P_{deagg}	257,244	39.9%	11,558
P_{deleg}	**93,754**	**14.6%**	**13,689**
P_{top}	40,475	6.3%	12,647

Table 2: Overview of prefix classes in d_{2016}.

Delegation class	#Prefixes	%Prefixes	#AS pairs
C_{down}	**56,294**	**60.0%**	**12,427**
$C_{isolated}$	27,016	28.8%	5,748
C_{up}	9,546	10.2%	1,183
$C_{crossed}$	898	1.0%	127

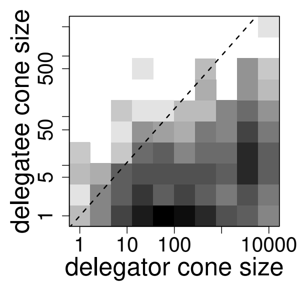
Table 3: Overview of delegation classes in d_{2016}.

its numbers have doubled in the past decade. Using d_{hist}, Figure 4(b) shows how much each of the delegation classes contribute to this increase. As expected, C_{down} has and has had the largest share with well over 50%. However, $C_{isolated}$ is a substantial contributor with more than 20% in the past decade. The largest increase is seen in the class C_{up}; it has grown by a factor of 5.1 over the past ten years. Considering d_{2016}, we confirm that C_{down} is the most common case with a share of 60%. However, $C_{isolated}$ and C_{up} are substantial with more than 29% and 10%, respectively. The smallest class, with a contribution of only 1%, is $C_{crossed}$.

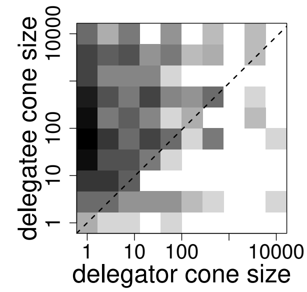
6. AS BUSINESS RELATIONSHIPS

The delegations from d_{2016} involve more than 16k delegators as well as delegatees, emphasizing that delegations are common practice. Also, they involve more than 19k AS pairs (delegator to delegatee), see Table 3. We observe that an AS pair can be involved in more than one delegation type.

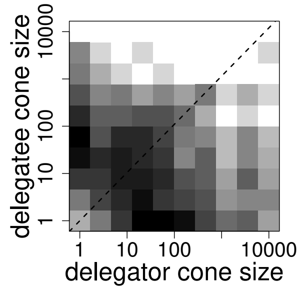
Delegation vs. AS size: We explore to which extent the four delegation classes align with the relative size of the two involved ASes. Hereby, we use the customer cone size as a proxy for the AS size using d_{cone}. Figure 5 shows four heat maps—one for each delegation class—with the cone size of the delegator (x-axis) vs. the cone size of the delegatee (y-axis).



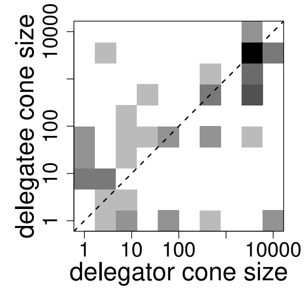
(a) C_{down}



(b) C_{up}



(c) $C_{isolated}$

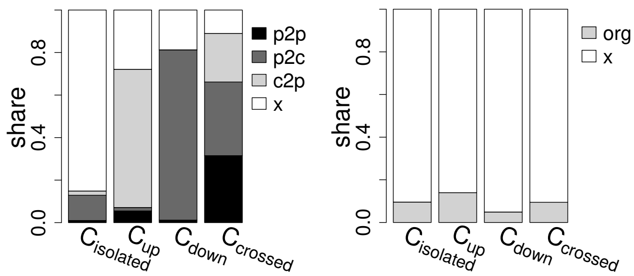


(d) $C_{crossed}$

Figure 5: Heat map per delegation class: delegator cone size vs. delegatee cone size. The gray scale indicates the density in log scale.

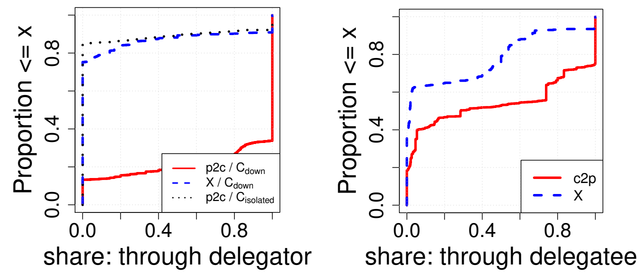
All delegation classes include ASes of varying AS sizes (from 1 to 10k+) both as delegatee and as delegator. We notice substantial differences. In C_{down} more than 99.5% of all delegators have a larger cone size than the delegatee. For C_{up} we see the opposite— in 93% the delegator has a smaller cone size than the delegatee. Thus, the delegated prefix is either originated by (C_{up}) or announced via (C_{down}) the AS with the larger cone size. The heat map for $C_{isolated}$ is not that focused on either the upper or lower half; we see a mixture. Some delegations take place between ASes with large cones to those with smaller cones and the other way around. $C_{crossed}$ shows a dense spot of AS pairs which have large customer cones. Examples include delegations between NTT America and Cogent, two ASes of Level 3, AT&T and Qwest, Qwest and Verizon, and AT&T and Level3. These mainly involve major ISPs and content delivery networks. Some of the delegations may be artifacts of mergers or internal network practices.

Business relationships: We next correlate prefix delegations with business relations using $d_{business}$. For each of the 19k AS pairs involved in prefix delegations, i.e., delegator and delegatee, we assign either a c2p, p2c, p2p relationship or label it with *x* if no relationship is included in the data. In any of the *x2y*-like assignments, *x* is the delegator and *y* the delegatee. Figure 6 shows barplots of the classification for each of the different delegation classes. Interestingly, we find that in 39.5% of the AS pairs, the delegator is not adja-



(a) business relationship (b) organizations

Figure 6: Barplot: delegations by business relationship and organization.



(a) C_{down} & $C_{isolated}$ (b) C_{up}

Figure 7: CDF: path selection

cent to the delegatee (34.4% of all delegations). In $C_{isolated}$ 85% of AS pairs are unclassified while the fraction in C_{up}, C_{down} and $C_{crossed}$ is less: 28% / 19% / 11%.

If we only consider delegations between adjacent ASes we find that 99% AS pairs in C_{down} have a p2c relationship. This is what one may expect and is consistent with our previous observations regarding the customer cone size differences. These are the ones that fall below the diagonal in Figure 5(a). Similar observations hold for C_{up}. 90.2% have the expected c2p relationship and indeed these are the ones that fall above the diagonal in Figure 5(b). The others are mainly p2p (7.6%) with only a small fraction of p2c (2.2%). $C_{crossed}$ includes the largest fraction of p2p relationships. This hints at mutual agreements between the two involved ASes which can result in such apparently unusual routing arrangements. It is not surprising that this class includes AS pairs where both have large customer cones. Overall, these results show that each delegation class involves a distinct variety of business relations among the ASes.

We acknowledge that some of the *x*-labeled AS pairs might be caused by AS links that are not visible in this data set. To mitigate the impact of such missing links, we use additional data sets, d_{mlp} and $d_{complex}$. However, we note that they only provide a minute number of additional AS links. In particular, out of the links in $d_{complex}$ we only find 38 and in d_{mlp} 49 additional links which corresponds to 1% of our *x*-labeled AS pairs. We discuss delegations among non-adjacent ASes in detail in Section 7.

Organizations: We also use the AS-to-organization mapping from d_{org} to check if most of the delegations occur between ASes of the same organization. The resulting barplot in Figure 6(b) shows that 10-15% of the AS pairs are within the same organization. The largest fraction are in C_{up} the smallest in C_{down}. However, this is by far not the majority.

7. EFFECTS ON PATH SELECTION

While BGP routing information provides multiple paths towards a destination the actual traffic follows the *best* path. To better understand how prefix delegations affect the traffic flow, we complement our analysis of prefix delegation classes with large-scale traceroute measurements from d_{trace}. We select two sets of traceroutes: those that target the delegated prefix P_{deleg}, and those that target non-overlapping parts of the associated/less specific P_{top}. We exclude traceroute results that do not reach the destination AS. For that we map IPs from d_{trace} to ASes by applying the longest prefix match using prefixes from d_{2016}. This results in traceroutes towards 56,543 (60%) of the delegated prefixes and towards 7,458 (70%) of the less specific prefixes. We refer to this set of traceroutes as d_{flow}. For each delegation covered by d_{flow} we determine the ratio of traceroutes going through the delegator / delegatee. We refer to it as the *pass-through rate* (*ptr*). Figure 7 shows the *empirical cumulative distribution* (CDF) of the resulting *ptrs*. In both plots we see that for some delegations the traceroutes always use the path through the delegator / delegatee (*ptr* is 1), for other delegations this is never the case (*ptr* is 0). In the following we analyze some of the delegation scenarios using this additional information.

PA prefixes from provider to customer: A common example of a delegation is in a p2c relationship, where the provider AS delegates PA address space to its customer AS. This delegation scenario falls into C_{down} if the provider announces both, the more and the less specific prefix. We find traceroutes for 29.1k of those delegations in d_{flow}. The solid line (p2c/C_{down}) in Figure 7(a) shows the corresponding *ptrs*. For 65% of those delegations the traceroutes always go via the delegating provider to the customer. A more detailed analysis shows that one third of the delegatees appear to be single-homed (cone size of 1). This contradicts best current practices as stated, e.g., in [20]. However, we also see the opposite: For roughly 15% the traceroutes never go through the delegating provider, but via an alternative one. We conclude, given the number of single-homed customers, there is significant potential for further address aggregation.

If however the provider only announces the less specific, it falls into $C_{isolated}$. Because opposite to the previous case, here the delegating provider aggregates the PA prefix with its own. Note that the customer must be multi-homed because despite aggregation, we can observe the delegated prefix. We find traceroutes for 1.3k of those delegations in d_{flow}. The dotted line (p2c/$C_{isolated}$) in Figure 7(a) shows the corresponding *ptrs*. For the majority (around 85%) of delegations the traceroutes towards the customer never pass through the delegating provider. However, in 10% of the delegations they always do, despite aggregation. This hints at either limited propagation of the more specific prefix or uncommon routing policies.

Next, we check if for delegations in C_{down} with non-adjacent ASes traceroute data provides additional information. Using d_{flow}, we find traceroutes for 2.6k delegations of this type. For around 75% we find no traceroute which goes through the delegator, see dashed line (*x*/C_{down}). Less than 10% always go through the delegator. Note that in this case 15% of the delegatees are in the customer cone of the delegator. This supports our claim that there are indirect business relationships among two involved ASes.

Delegations from customer to provider: Next, we explore the case where the customer AS delegates prefixes to its provider. This involves 80.4% of the delegations in C_{up}, 31.4% in $C_{crossed}$ and 3.7% in $C_{isolated}$. These findings contrast previous work [20] where the authors state that delegations from customer to provider are unlikely to be found in the Internet. While we find many customer ASes delegating single prefixes to providers, we also see some ASes delegating hundreds of prefixes. The latter involves, e.g., delegations within organizations or CDNs. Recall, the number of delegations in this class has grown the most over the past ten years indicating the need for such services.

We find traceroutes for 5.2k of those delegations (c2p/C_{up}) in d_{flow}. The solid line in Figure 7(b) shows the CDF of the corresponding *ptrs*: For 57% some traceroutes go through the delegatee and others do not, i.e., the *ptr* is between 0 and 1. In only 25% of the delegations the traceroutes always pass through the provider. For the remaining 18%, none of the traceroutes do. Using d_{flow} again, we find traceroutes for further 1.3k C_{up} delegations among non-adjacent ASes (*x*/C_{up}). Here we observe a similar behavior: For more than 60% of those delegations the corresponding *ptr* is between 0 and 1, see dashed line in Figure 7(b).

Compared to the delegations of PA prefixes from provider to customer, here the path selection of the traceroutes is less consistent. While for roughly 20% of the delegations in Figure 7(a) the *ptr* is between 0 and 1, it is roughly 60% of the delegations in Figure 7(b). We conclude that depending on the type of delegations, i.e., how prefixes are announced by the delegator and delegatee, the path selection of traceroutes is noticeably affected.

Delegations among non-adjacent ASes: 34% of the delegations involve AS pairs without any AS link (recall Section 6). The majority is in $C_{isolated}$ where no announcements pass through the involved ASes. This is confirmed by the traceroute data, i.e., in around 90% of $C_{isolated}$ delegations, the traceroute never goes via the delegator or the delegatee (plot not shown). In order to underline the diversity of prefix delegations, we present case studies comparing a large ISP (Comcast) and a large CDN (Akamai). Also, we look at a small organization operating at global scale.

Often organizations use several ASes, e.g., AT&T. Yet, it appears that only a single AS (or a small number of ASes) is used to delegate prefixes to other organizations. For example: between 2011 and 2014 the Akamai AS_{31377} delegated more than 2,000 prefixes to several non-adjacent Tier-1 ASes world-wide (C_{up}) and to other Akamai ASes. After its disappearance from the routing system in 2014 AS_{31377} was replaced by AS_{35994}. In January 2016 AS_{35994} delegated more than 4,000 prefixes to more than 100 ASes. We find that these delegations are volatile. Figure 8(a) shows the churn in delegations over time for AS_{31377} using d_{hist}. Whenever we observe a delegation for the first time we label it *new*. As long as a prefix keeps being announced we label it *stable* until it disappears. If it reappears it is in *recurrent*. Supported by the high increase of delegations and the irregular but high growth of new delegations, AS_{31377} often delegates and revokes delegations. This is in contrast to AS_{7922} (Comcast) where the number of stable prefixes decreases slower over time, see Figure 8(b).

Next, we compare the customer cone size distribution of delegatees of AS_{31377} and AS_{7922}, using d_{cone} data from 2014. We consider only delegations to delegatees in organizations different from the delegator. While AS_{7922} delegates 170 prefixes to 154 unique delegatees (all US organizations), AS_{31377} delegates 2,062 prefixes to 95 delegatees, worldwide. Both ASes mainly delegate to non-adjacent delegatees, i.e., 93.5% for AS_{7922} and 97.9% for AS_{31377}. While for AS_{7922} most delegations are in C_{down} for AS_{31377} all are in $C_{isolated}$ or C_{up}. Figure 8(c) shows the CDF of the delegatee cone size for both ASes. We observe that for AS_{7922} more than 97% have a cone size of 1. The distribution for AS_{31377} differs significantly as roughly 50% have a cone size larger than 100.

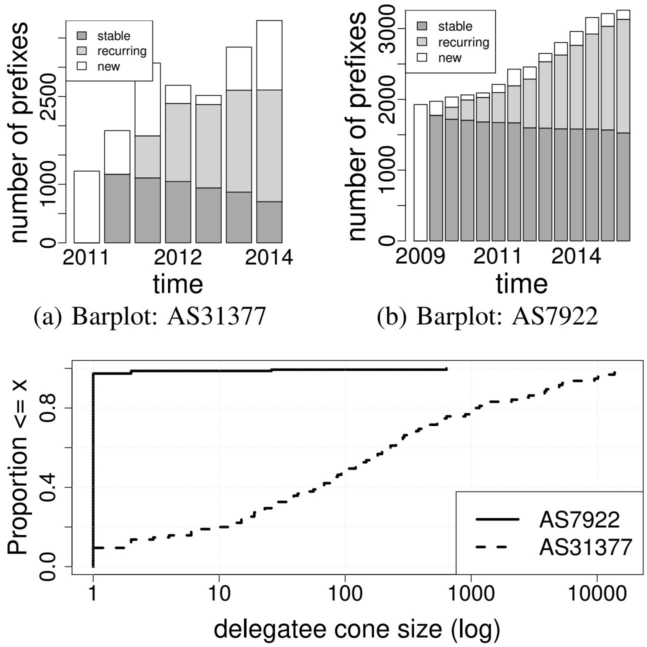
In order to show that these versatile delegations are not limited to big organizations, we next study a hotel company: Fairmont Hotels & Resorts Inc. owns a /16 according to WHOIS and its address space is maintained by 'Q9 Networks - Canada's data centre'. They use a conglomeration of different delegation strategies: The main Q9 AS (AS_{12188}) appears to delegate all prefixes to its upstream providers, i.e., Cogent, Qwest, Bell Ca, and Shaw (C_{up}). In addition, we find intra-organization delegations to other ASes, which are connected to yet another set of large ASes including Tinet SpA. Furthermore, there are a lot of $C_{isolated}$ delegations to ASes in several locations, e.g., Canada, US, Mexico, Bermuda, Singapore. Other delegatees are Level3 and Verizon.

8. SUMMARY

To better understand the growth of the global routing table we study one of its constituents: delegated prefixes. By distinguishing between different delegation classes we are able to characterize a diverse ecosystem: We find delegations from provider to customer (53%) and from customer to provider (10%), e.g., for traffic engineering. Another 34% of the delegations are between non-adjacent ASes. Our analysis reveals the existence of indirect business relationships among the involved ASes. Other ASes delegate to distant ASes to realize global services, e.g., CDNs.

These results highlight that delegations are not limited to PA address space to a customer. They indicate delegation of address space up and across the AS level hierarchy. Also, delegations have a noticeable impact on the traffic flow: By analyzing traceroute paths towards the delegator / delegatee we find that delegations from customer to provider cause a more unpredictable selection of ingress paths, as compared to, e.g., delegations from provider to customer.

Using case studies we contrast the delegation habits of a large ISP, a large CDN, and a small organization. Com-



(a) Barplot: AS31377 (b) Barplot: AS7922

(c) CDF: delegatee customer cone size distribution

Figure 8: Case studies—Large ISP/large CDN: Churn and cone size distribution.

pared to the ISP, delegations performed by the CDN are more volatile: Over time we observe many new and reused delegations as well as their disappearance. Also, we find that the ISP often delegates to local organizations while the delegatees of the CDN are globally distributed. Delegations, however, are not limited to big organizations but are commonplace among ASes of any size. Thus, supported by our historical analysis, we conclude that the routing table will continue to grow as an increasing number of announcements become unaggregatable.

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