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Quantifying AS Path Inflation by Routing Policies

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Abstract

A route in the Internet may take a longer AS path than the shortest AS path due to routing policies. In this paper, we systematically analyze AS paths and quantify the extent to which routing policies inflate AS paths. The results show that AS path inflation in the Internet is more prevalent than expected. We first present the extent of AS path inflation observed from the RouteView and RIPE routing tables. We then employ three common routing policies to show the extent of AS path inflation. We find that No-Valley routing policy causes the least AS path inflation among the three routing policies. Prefer-Customer-and-Peer-over-Provider policy causes the most AS path inflation. In addition, we find that single-homed stub ASes experience more path inflations than transit ASes and multi-homed ASes. The AS pairs with shortest AS path of 3 AS hops experience more path inflations than other AS pairs. Finally, we investigate the AS path inflation on the end-to-end path from end users to two popular content providers, Google and Comcast. Although the majority of the shortest AS paths from end users to the two providers consists of no more than three AS hops, the actual end-to-end paths that the traffic will take are longer than the shortest AS paths in many cases. Quantifying AS path inflation in the Internet has important implications on the extent of routing policies, traffic engineering performed on the Internet, and BGP convergence speed.

***Keywords**: path inflation, routing policy, inter-domain routing, BGP, autonomous systems, measurement.*

1. Introduction

The Internet connects thousands of Autonomous Systems (ASes) operated by different Internet Service Providers (ISPs), companies, and universities. Routing within an AS is controlled by intra-domain protocols such as static routing, OSPF, IS-IS, and RIP. Border Gateway Protocol (BGP) [1, 2] is an inter-domain routing protocol that allows ASes to apply local policies for selecting routes and propagating routing information. These routing policies are typically constrained by contractual commercial agreements between administrative domains. It is well known that an AS may take a longer AS path than the shortest AS path possibly as a result of these routing policies. However, the extent to which routing policies inflate AS paths in the Internet has not been systematically analyzed or quantified.

Quantifying AS path inflation in the Internet has important implications on the extent of routing policies and traffic engineering performed on the Internet, and BGP convergence speed. First, since ISPs typically do not make their routing policies public, it is not clear how prevalent these routing policies are and to what extent AS paths are inflated due to routing policies. Second, BGP protocol studies [3, 4] have shown that BGP convergence speed is directly correlated with AS path length. The extent of AS path inflation indicates the extent to which routing policies can increase BGP convergence

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time. Third, con- tent providers such as Google or Content Delivery Networks (CDN) such as Akamai move the content closer to the end user to reduce the origin content server and improve performance for clients. Most of the studies on the content placement, such as [5, 6], focus on router-level path or the shortest AS paths. However, the actual paths taken by packets are not necessarily the shortest AS paths. Hence, the content placement selection needs to take actual AS paths into consideration.

In this paper, we first systematically study AS paths and quantify the extent that AS paths are inflated by routing policies. Our results show that AS path inflation in the Internet is more prevalent than expected. We derive chosen AS paths and shortest AS paths based on BGP routing tables collected from the Route View and RIPE RIS projects [7, 8]. In particular, we collect statistics of AS path length from ISPs of various sizes: tier-1 ISPs, tier-2 ISPs, and tier-3 ISPs. From 12 tier-1 ISPs, more than 30% of the chosen AS paths are longer than the shortest AS paths and AS paths can be inflated by as long as 5 AS hops. From the selected tier-2 ISPs, at least 47% of chosen AS paths are longer than the shortest AS paths and AS paths can be inflated by as long as 6 AS hops. From the selected tier-3 ISPs, more than 50% of chosen AS paths are longer than the shortest AS paths and AS paths can be inflated by as long as 6 AS hops.

And then, we present three common routing policies to show the extent to which an AS path can be inflated by the routing policies. The three common routing policies are described as follows. First, it is typical that an AS does not transit traffic between its providers or peers. This is referred to as No-Valley routing policy. Our results show that this routing policy inflates AS paths for only 4% of the AS pairs. Second, it is common that an AS prefers its customer route over its provider or peer routes. This is referred to as the Prefer-Customer routing policy. Third, it is common that an AS prefers its peer routes over its provider routes. This is referred to as the Prefer-Customer-and-Peer-over-Provider routing policy. We derive AS paths that conform to the second and the third routing policy, and find that more than 45% of AS pairs use a longer AS path than the shortest AS path. In other words, significant inflation of AS paths is due to the Prefer-Customer and Prefer-Customer-and-Peer-over-Provider routing policies.

Finally, we investigate the AS path inflation on the end-to- end path from end users to two content providers, Google and Comcast. The two content providers have their own global backbones and directly peer/connect with many consumer net- works. We find that the majority of the shortest AS paths from end users to Google or Comcast consist of no more than three AS hops. Note that the average AS path length in the Internet is about 3.9 hops [9]. However, we find that the Prefer- Customer and Prefer-Customer-and-Peer-over-Provider routing policies inflate the end-to-end paths, with over 10% of the paths longer than the shortest AS path. That means, the actual path that the traffic will take can be longer than shortest AS path in many cases.

Several works have been focused on path inflation. In [10], the authors measure the path inflation accounting for the popularity of Internet traffic destinations. Work [11] proposes an overlay routing infrastructure to eliminate path inflation due to the inter-domain routing policy. Work [12] focuses on solving path inflation occurring in generalized chordal graphs. In [13], the authors propose a local path inflation metric that does not rely on global AS graph and show that the local path inflation values can be very diverse among different ASes. Tangmunarunkit et al. studied the Internet path length [14], and assumed that each AS chooses the shortest AS path. With this assumption, the authors conclude that 20% of Internet paths are inflated by more than five router-level hops. Work [15] studied the root causes of path inflation from the intra- and inter-domain ISP points of view and from the ISP peering relationship. Our study complements their work by focusing on AS path inflation instead of router level hop inflation. In addition, we quantify AS path inflation by analyzing real BGP routing tables and explore routing policies that conform to commercial relationships. In addition, several works have been focused on inferring AS-level paths. In [16], Mao et al. investigate the feasibility of inferring AS-level path without direct access to end-points. In [17], Sobrinho et al. presented an algebraic theory to understand the minimum number of links in a network whose failure causes the network to become disconnected.

The remainder of the paper is structured as follows. In Section 2, we quantify the extent of AS path inflation in the Internet by analyzing BGP routing tables. Section 3 presents AS path inflation for some selected AS pairs by examining three typical routing policies guided by commercial relationships. We derive the extent to which AS paths are inflated by these routing policies for those AS pairs. In Section 4, we investigate the path inflation occurring at Google and Comcast. We conclude the paper in Section 5 with a summary.

2. AS Path Inflation

In this section, we quantify the extent of AS path inflation in the Internet. To this end, we construct an AS graph G = (V, E), where the node set V consists of ASes and the edge set E consists of AS pairs that exchange traffic with each other. And then, we derive the chosen AS path length and the shortest AS path length between a pair of ASes. The shortest path between a pair of ASes can be derived by using Dijkstras algorithm [18], and the chosen AS path can be obtained from BGP routing tables.

2.1. Data Sets

We use BGP routing tables from the RouteViews [7] and the RIPE RIS [8] to construct the AS graph. RouteView and RIPE RIS contain hundreds of BGP monitors to collect BGP data. We download daily dumps of BGP tables from all monitors deployed by RouteViews and RIPE RIS. We analyze routing tables during year 2012 and 2013, and present the results for 05/01/2013 only throughout this paper since the results for other dates are similar.

According to previous work, we also notice that a significant number of existing AS connections cannot be seen in BGP routing tables according to previous work [19 - 21]. To address this problem, we collect AS Links Dataset provided by CAIDA [22], which adds 44,424 more AS links to the AS graph. Note that although some AS level connections might not be included in the AS graph constructed from Route Views, this can only result in an overestimation of shortest AS path length.

2.1. Multiple Vantage Points

To demonstrate the AS path inflation from different ASes, we illustrate the extent of AS path inflation from different vantage points – all AS pairs whose chosen AS paths are visible from the RouteView and RIPE routing tables. The routing tables in 05/01/2013 contains 424 BGP monitoring peers. We classify those BGP monitoring nodes into three classes: tier-1 ASes, tier-2 ASes, and tier-3 ASes. An AS is called a tier-1 AS if it accesses the global Internet and does not buy network capacity from other ASes. Providers that buy part or all of their inter-connectivity from tier-1 ASes are tier-2 ASes. A local AS is defined as a tier-3 AS. We classify those nodes into 3 tiers as follows. We start with the 12 well-known tier-1 ASes. Those ASes whose providers are all tier-1 ASes are then classified as tier-2 ASes. We also ensure that those tier-2 ASes have customers. At last, we classify other ASes that have customers as tier-3 ASes. We select 12 tier-1 ASes, 105 tier-2 ASes, and 28 tier-3 ASes to investigate AS path inflation. All of those selected ASes provide default-free BGP tables. Next, we present the measurement results for each type of ASes.

2.3. AS Path Inflation Measurement

The chosen AS path length between a pair of ASes is computed by the AS path appearing in the BGP routing table. We eliminate the AS prepending effect on the routing table. In other words, if an AS appears in an AS path several times, then we count the AS only once in the AS path length. Since an AS pair might use different AS paths for different destination prefixes, we choose to use the shortest for the chosen AS path length to see the extent of AS path inflation.

2.3.1. Tier-1 ASes

To quantify the difference between the chosen AS path length and the shortest AS path length from 12 tier-1 ASes, we plot the percentage of AS pairs whose chosen AS paths are inflated by a fixed number in Figure 1. Note that we use error bars in Figure 1 to represent the minimum, maximum, and median, respectively, of the path inflation. The figure shows that more than 30% of the selected tier-1 ASes' paths are inflated by at least one AS hop in 2013, and the majority of the paths are inflated by one AS hop. We also notice that Figure 1 does not exhibit a large variation in AS path inflation cross the 12 selected tier-1 ASes. For example, less than 23% of AS 209's paths are inflated, which has the least number of path inflation, while more than 40% of AS 6939's paths are inflated, which has the largest number of path inflation.

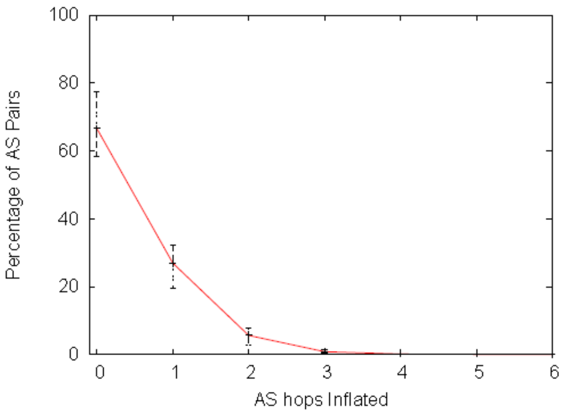


Figure 1. The Distribution of Overall AS Path Inflation on the AS-Level Paths to 12 Tier-1 Ases

Figure 2 shows the distribution of overall path inflation with respect to the shortest AS path. We see that most AS path inflations occur within AS path length 2 to 3, and most AS paths are inflated by one hop. In addition, we see that some tier-1 ISPs are 2 AS hops to other ASes in the shortest path while it can be as long as 7 hops in the chosen path.

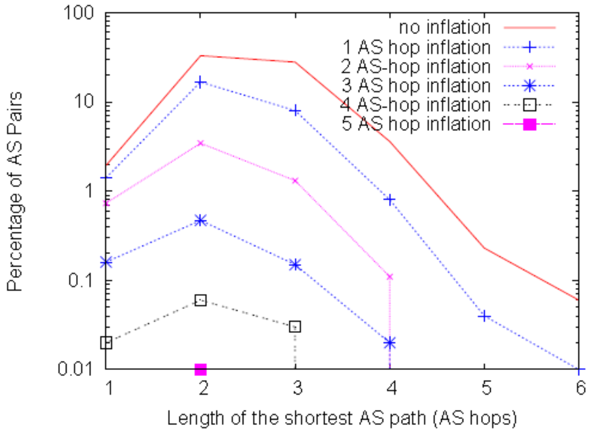


Figure 2. The Distribution of Overall AS Path Inflation With Respect to the Shortest AS Path for 12 Tier-1 Ases

2.3.2. Tier-2 ASes

In Figure 3, about 47% of those AS pairs have a longer chosen AS path than the shortest AS path, and the AS path from those tier-2 ASes can be inflated by more than 12 AS hops. Similar to the path inflation from the tier-1 ASes, we do not observe a large variation in one AS hop and two AS hops inflation. For example, about 30% of AS 20640's chosen paths are inflated by at least one AS hop, while 56% of AS 48166's chosen paths are inflated by at least one AS hop.

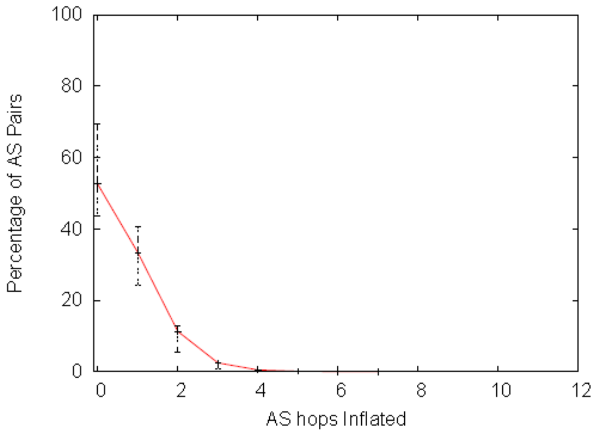


Figure 3. The Distribution of Overall AS Path Inflation on the AS-Level Paths to the Selected Tier-2 Ases

Figure 4 shows that from the selected tier-2 ASes, most inflations occur within AS path length 2 to 4, and the chosen AS paths can be as long as 9 hops from the tier-2 ASes while the shortest AS paths are at most 3 hops. Note that the AS path inflation is more significant for the tier-2 ASes than for the tier-1 ASes. This means that the AS paths from the tier-2 ASes are affected by routing policies more severely than the tier-1 ASes are.

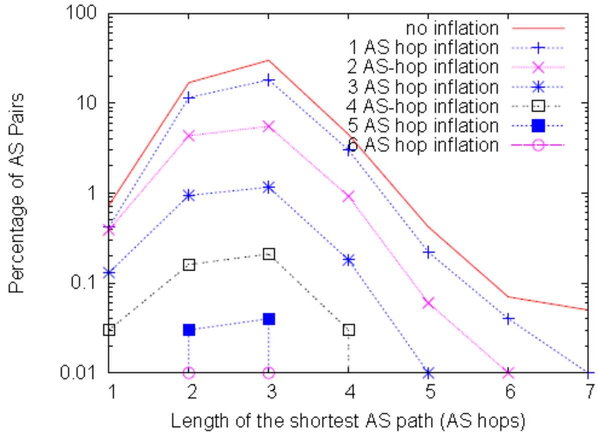


Figure 4. The Distribution of Overall AS Path Inflation With Respect to the Shortest AS Path for the Selected Tier-2 Ases

2.3.3. Tier-3 ASes

In Figure 5, about 50% of the chosen AS paths from those tier-3 ASes are longer than the shortest AS paths, and AS paths can be inflated by as long as 12 AS hops. Different with the tier- 1 and tier-2 ASes, we observe a large variation in path inflation. For example, less than 20% of AS 22873's chosen AS path are longer than the shortest AS path, while more than 76% of AS 38809's chosen AS path are longer than the shortest AS path. At the same time, we observe that about 50% of AS 48285's chose AS paths are inflated by at least one AS hop. Therefore, AS path inflation is more severe from the tier-3 ASes than from the tier-1 and tier-2 ASes. Figure 6 shows that most AS path inflations occur within AS path length 2 to 4. We see that the chosen AS paths can be as long as 9 AS hops while the shortest AS path is at most 3 AS hops.

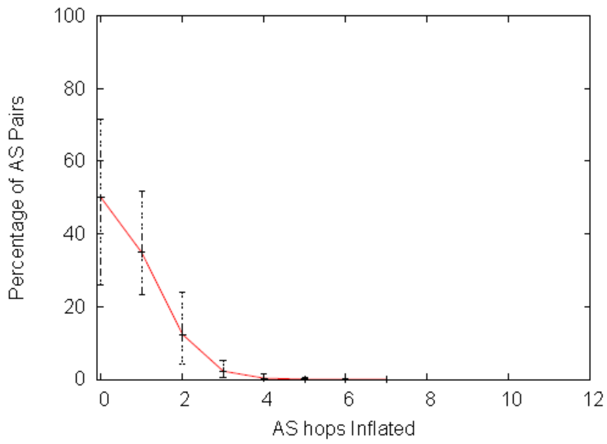


Figure 5. The Distribution of Overall AS Path Inflation on the AS-Level Paths to the Selected Tier-3 Ases

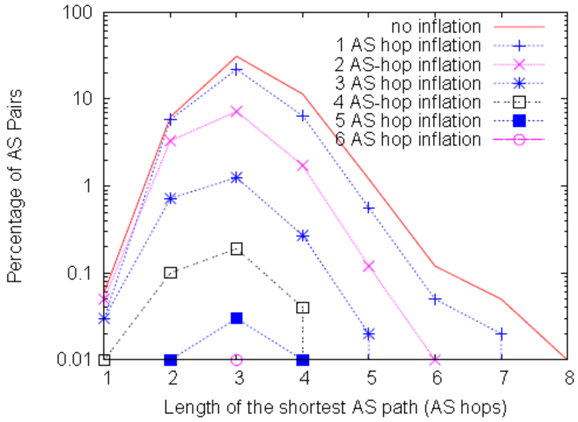


Figure 6. The Distribution of Overall AS Path Inflation with Respect to the Shortest AS Path for the Selected Tier-3 Ases

2.4. Impact of Missing Links on AS Path Inflation

Previous work shows that missing links from RouteView can result in an overestimation of shortest AS path length [19, 20, and 21]. Here, we investigate the extent to which the missing links from RouteView and RIPE routing tables can impact the AS path inflations. We first compute AS path inflation based on the routing tables from RouteView and RIPE, and we define this result based on an incomplete AS graph. And then, we add 44,424 links from CAIDA traceroute to construct a new AS graph, and derive new AS path inflation results based on the augmented AS graph. Combining the BGP tables from the three datasets results in an AS graph with 41,931 nodes and 8,161,010 edges. We compare the two results by calculating the AS hop difference between the two path Inflations. Figure 7 shows the over-estimation of AS hop inflations derived from the incomplete AS graph. We observe that less than 10% of path inflations are overestimated in the incomplete AS graph. In other words, the majority of the path inflations can be correctly derived from the incomplete AS graph. This observation is intuitively understandable: the majority of peering ISPs in RouteView and RIPE are tier-1, tier-2, and tier-3 ISPs so that the peer-to-peer links among those ISPs can be observed from a BGP routing table. Those extra links from CAIDA are mainly between smaller ISPs so that they impact a limited number of AS pairs.

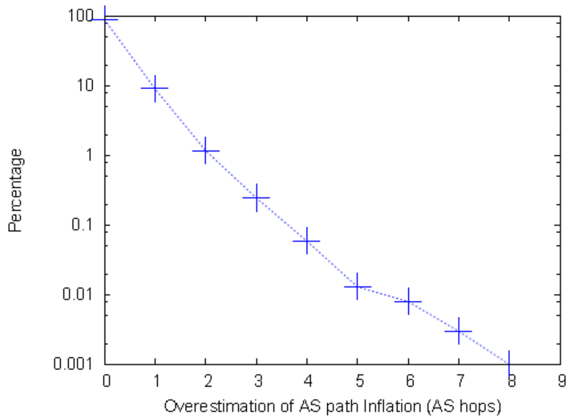


Figure 7. Impact of Missing Links from Routeview and RIPE On AS Path Inflation

3. AS Path Inflation by Routing Policies

From the previous section, we can see that the extent of AS path inflation varies from ASes to ASes. Because not all ISPs are willing to reveal their routing policies, it is hard to get an overall picture of the AS path inflation. From our data sets, we compare the chosen AS paths from only 145 peers in 2013. To better understand the AS path inflation in the Internet, we infer AS-level end-to-end paths by assuming three typical routing policies. We present the three routing policies that conform to commercial contractual agreements. And then, we compare the derived AS path length with the shortest AS path length.

3.1. Routing Policies

Routing policies typically conform to the commercial relationships between ASes. A customer pays its provider for connectivity to the rest of the Internet. A pair of peers agree to exchange traffic between their respective customers free of charge. A mutual-transit agreement allows a pair of administrative do- mains to provide connectivity to the rest of the Internet for each other.

The commercial contractual relationships between ASes translate into the export rule that an AS does not transit traffic between two of its providers and peers. Formally, we define customer (a), peer (a), and provider (a) as the set of customers, peers, and providers of a, respectively. We classify the set of routes in an AS into customer, provider, and peer routes. A route r of AS u is a customer (provider, or peer) route if the first consecutive AS pair in r.as_path has a provider-to-customer (customer-to-provider, or peer-to-peer) relationship. More precisely, let r.as_path = (u1, u2. . . un). If (u1, u2) is a provider-to-customer (customer-to-provider or peer-to-peer) edge, then r is a customer (provider or peer) route. An AS selectively provides transit services for its neighboring ASes. The selective export rule translates into a No-Valley routing policy. Intuitively, if we imagine that a provider is always above its customers and two peering ASes are at the same level, then once an AS path goes down or remains at the same level, it does not go up or remain at the same level.

Furthermore, a route r is classified as a customer route of a if first(r.as_path)□ customer(a), a private-peer route if first(r.as_path) □ peer(a), or a provider route if first(r.as_path)□provider(a). The AS relationships translate into the following rules that govern BGP export policies [23, 24]; we refer to these rules as the selective export rules.

- Exporting to a provider: In exchanging routing information with a provider, an AS can export its routes and its customer routes, but usually does not export its provider or peer routes. That is, an AS does not provide transit services for its provider.
- Exporting to a customer: In exchanging routing information with a customer, an AS can export its routes and its customer routes, as well as its provider and peer routes. That is, an AS does provide transit services for its customers.
- Exporting to a peer: In exchanging routing information with a peer, an AS can export its routes and its customer routes, but usually does not export its provider or peer routes. That is, an AS does not provide transit services.

As a result of the above export polices, paths received by an AS have the no-valley property. In a no-valley path, after traversing a provider-to-customer or peer-to-peer edge, it cannot traverse a customer-to-provider or peer-to-peer edge. In other words, after traversing a provider-to-customer or peer-to-peer edge, the AS path must traverse provider-to-customer edges. That is, in a no-valley AS path (u1, u2, . . . , un), there is i such that $0 \le i < n + 1$ and for all $0 < j < i$, (u j, u j+1) is a customer-to-provider edge, (u j, u j+1) must be a provider-to-customer edge for any $i + 1 < j < n$, and (ui+1, ui+2) can be either a peer-to-peer or provider-to-customer edge. For example, in Figure 8, AS paths (1, 4, 6, 2) and (1, 4, 5) are no-valley paths while as path (4, 5, 2) and (4, 1, 2, 6) are not no-valley paths. Note that the selective export rule ensures that BGP routing table entries contain only no-valley AS paths. For example, if AS path (1, 4, 3) appears in a BGP routing table, then AS 4 exports its provider route (3) to its provider AS 1. This violates the selective export rule.

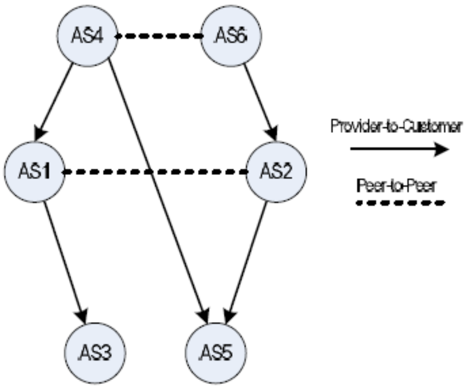


Figure 8. An Annotated AS Graph Representing Contractual Relationships Be-Tween Connected Ases

In addition to the no-valley routing policy, an AS typically chooses a customer route over a route via a provider or peer since an AS does not have to pay its customer to carry traffic or maintain a traffic volume ratio between the traffic from and to a peer. In addition to the prefer-customer property, an AS might choose a peer route over a provider route since an AS has to pay for the traffic its provider carries for it. Note that these import polices do not restrict the preference among customer routes or among provider or peer routes, which provides ISPs with significant flexibility in selecting local policies. Formally, we have the following import policies for AS a:

- Prefer-customer: If first(r1 .as_path) ∈ customer(a) and first(r2 .as_path) ∈ peer(a) ∪ provider(a), then r1.loc_pre f > r2.loc_pre f .
- Prefer-peer-over-provider: If first(r1 .as_path) ∈ peer(a) and first(r2 .as_path) ∈ provider(a), then r1.loc_pre f > r2.loc_pre f .

Note that each AS has economic incentive to follow the import routing policies, since traffic through a provider route will lead to payment to the provider. Further, these routing policy guidelines can ensure routing stability of the global Internet [25].

3.2. Three Common Routing Policies

We have the following three common routing policies.

- No-Valley Routing Policy: each AS exports all routes that follow the selective export rule. Furthermore, each AS sets local preference for all routes to be the same. That is, each AS chooses an AS path that is the shortest among received paths.
- Prefer-Customer Routing Policy: each AS exports all routes that follow the selective export rule. Furthermore, each AS follow the prefer-customer import policy, and the local-preference of all customer routes is the same, and the local-preference of all provider and peer routes is the same.
- Prefer-Customer-and-Peer-Over-Provider Routing Policy: each AS exports all routes that follow the selective export rule. Furthermore, each AS follows the prefer-customer and prefer-peer-over-provider import policy, and the local-preference of all customer routes is the same, the local-preference of all peer routes is the same, and the local-preference of all provider routes is the same.

Note that these three routing policies are the simplest routing policies that conform to routing policy guidelines. In reality, an AS can specify a diverse set of routing policies including its preference on customer (peer or provider) routes and filtering policies. For example, an AS can specify that it prefers routes through one of its neighbors over others. As we will see later our algorithms for Prefer-Customer and Prefer-Customer-and-Peer-Over-Provider Routing Policies can be expanded to more routing policies that conform to the guidelines.

3.3. Computing Policy-conforming Paths

Based on these common routing policies, we have three different policy-conforming paths: 1) No-Valley paths which are derived from the no-valley routing policies, 2) Prefer-Customer paths which are derived from the Prefer-Customer routing policy, and 3) Prefer-Customer-and-Peer-Over-Provider paths which are derived from the Prefer-Customer-and-Peer-Over-Provider routing policy. In this subsection, we show how to compute the policy-conforming paths for common routing policies.

First, we briefly present an algorithm to derive the no-valley paths for each node. We refer the reader to [26] for more de-tails on the algorithm, but we summarize how to use the algorithm for no-valley paths. Since each node does not have the Prefer-Customer routing policy, essentially, it will choose the shortest path among the paths received from its neighbors. More specific, we use the similar mechanism as the Dijkstra's algorithm to ensure that each node always chooses the shortest path received. Each node keeps track of all the paths received from neighbors and their corresponding type. The node with the shortest chosen path is selected. Once selected, the node propagates its paths to all its neighbors based on the type of path. Despite the fact that each node chooses the path among the paths received, it will still propagate the chosen path in a way that is consistent with the No-Valley policy. That is, it announces all paths to customers, but the paths learned from customers will be announced to providers and peers. We select nodes to finalize their no-valley paths based on the length of their chosen paths. This algorithm traverses each edge of the annotated AS graph at most twice. Further, selecting nodes with shortest path requires N log N time (if we use a heap to store the information of each node path length), where N is the number of nodes in the annotated AS graph. Therefore, it takes O(E + N log N) time to compute no-valley paths from all ASes to a destination AS, where N and E are the number of ASes and edges, respectively, in the annotated AS graph. For all pair AS paths, it takes O(NE + N2 log N) time to compute AS paths from all ASes to all destination ASes.

Second, we present an algorithm to derive the prefer-customer paths for each node. We refer the reader to [26] for more details on the algorithm. In order to compute the shortest Prefer-Customer path, we perform breadth-first search on the AS graph from d, which consists of provider-customer relationships only. That is, the graph is the DAG where the edge of the graph goes from customer to provider. In particular, we find the shortest path from d to all other nodes by performing breadth-first search on the AS graph from d. As long as there is at least one path that contains customer-to-provider edges but does not contain any provider-to-customer or peer-to-peer edge, the shortest Prefer-Customer path is derived by reversing the path discovered. If there are no Prefer-Customer paths, the shortest paths from d to all other nodes are the Prefer-Customer paths.

Similar to the algorithm for computing Prefer-Customer paths, we compute a Prefer-Customer-and-Peer-Over-Provider path by using a path that contains only provider-to-customer edges, and a path that first traverses a peer-to-peer edge and then traverses zero, one or more provider-to-customer edges. If such a path does not exist, we derive Prefer-Customer-and-Peer-Over-Provider paths based on a path that first traverses a peer-to-peer edge and then traverses zero, one or more provider-to-customer edges, and a path that contains one or several customer-to-provider edges, followed by zero or one peer-to-peer edge, followed by zero, one or several provider-to-customer edges. The key difference here is that Prefer-Customer-and-Peer-Over-Provider paths are the shortest step if such a path exists. We refer the reader to [26] for more details on the algorithm.

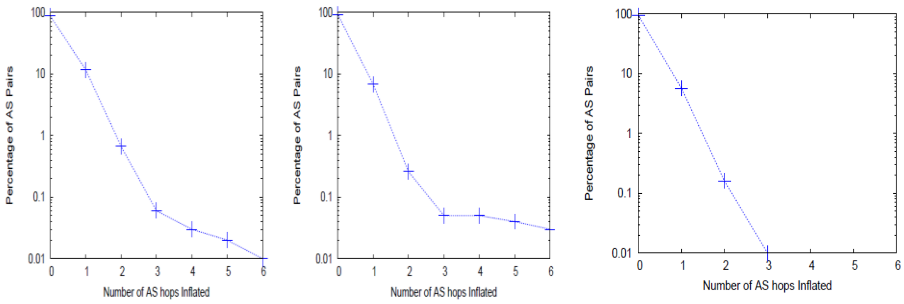
Both the algorithms of computing prefer-customer paths and prefer-customer-peer-over-provider paths traverse each edge of the annotated AS graph at most twice. Therefore, it takes O(E + N) time to derive the desired paths from all ASes to a destination AS, where N and E are the number of ASes and edges, respectively, in the annotated AS graph. For all pair AS paths, it takes O((E + N)N) time to compute AS paths from all ASes to all destination ASes.

3.4. AS Path Inflation due to Routing Policy

In this section, we present our measurement on path inflation due to the three common routing policies. Instead of investigating all AS pairs in the Internet, we focus on understanding the AS path inflation on end-to-end paths due to the routing policies. In particular, we investigate three different classes of ASes: transit ASes, single-homed ASes, and multi-homed stub ASes. We investigate 14,156 single-homed stub ASes and 14,060 multi-homed stub ASes from RouteView and RIPE routing tables in 2012, and 15,693 single-homed stub ASes and 13,538 multi-homed stub ASes in 2013. In addition, we consider all the ISPs that peer with RouteView and RIPE as transit ASes. Note that we present the results for 2013 only in this section since the results for other dates are similar.

3.4.1. AS Path Inflation due the No-valley Routing Policy

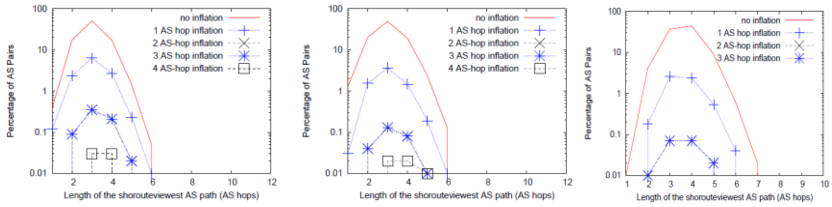
We first infer the AS relationships, and then perform our algorithms described above to derive the policy-conforming paths. The AS relationship inference algorithm in [27] is adopted in this paper. We compare the AS path length with the shortest AS path length given the No-valley routing policy. In Figure 9, about 6% of AS pairs for multi-homed ASes, 13%of AS pairs from transit ASes, and 7% of AS pairs from single-homed ASes have longer No-Valley AS paths than the shortest AS paths. The figure implies that the No-Valley policy does not cause path inflation significantly.



(a) Transit ASes (b) Single-homed ASes (c) Multi-homed ASes

Figure 9. AS Path Inflation Due to the No-Valley Routing Policy

From Figure 10(a), for transit ASes, we see that the AS paths derived from the No-Valley policy can be inflated by as long as 8 AS hops while the shortest AS paths are at most 4 AS hops. From Figure 10(b), for single-homed ASes, we see that the AS paths derived from the No-Valley policy can be inflated by as long as 9 AS hops, while the shortest AS paths are at most 5 AS hops. From Figure 10(c), for multi-homed ASes, we observe that the AS paths derived from the No-Valley policy can be inflated by as long as 8 AS hops while the shortest AS paths are at most 5 As hops.



(a) Transit ASes (b) Single-homed ASes (c) Multi-homed ASes

Figure 10. A Comparison of AS Paths Derived from the No-Valley Policy and Shortest AS Paths for all Selected AS Pairs

In summary, we see that there is a small discrepancy between the shortest AS paths and derived No-Valley AS paths. This indicates that ASes typically employ more complicated routing policies than the No-Valley routing policy.

3.4.2. Inflation Due to the Prefer-Customer and Prefer-Customer-and-Peer-Over-Provider Routing Policies

We see that the No-Valley routing policy does not inflate AS path significantly. This leads us to study two more sophisticated routing policies: Prefer-Customer and Prefer-Customer-and-Peer-over-Provider routing policies.

Before we present the measurement results, we use an ex-ample to demonstrate the path inflations occurring at a transit AS, a single-homed AS, and a multi-homed AS when all those ASes use Prefer-Customer or Prefer-Customer-and-Peer-over-Provider routing policy. In Figure 11, AS 6461 and AS 7018 are transit ASes. The two ASes have one customer AS, respectively. AS 1280 is a single-homed AS, and AS 6102 is a multi-homed AS. The shortest path from AS 6461 to the destination d is path (6461 7018 31817 d). The policy-conforming path derived by Prefer-Customer and Prefer-Customer-and-Peer-over-Provider routing policies is path (6461 46887 14985 31817 d). This transit AS (AS 6102) has one AS hop inflation. For the single-homed AS (AS 1280), the shortest path is (1280 6461 7018 31817 d), and the policy-conforming path is path (1280 6461 46887 14985 31817 d). The single-homed AS has one AS hop inflation. For the multi-homed AS (AS 6102), the shortest path is (6102 7018 31817 d), and policy-conforming path is path (6102 7018 31817 d). Thus, the multi-homed AS does not have any path inflation. This example shows that multi-homed ASes tend to have less path inflations than single-homed ASes.

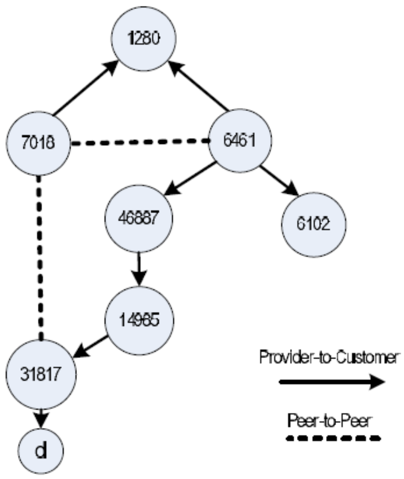
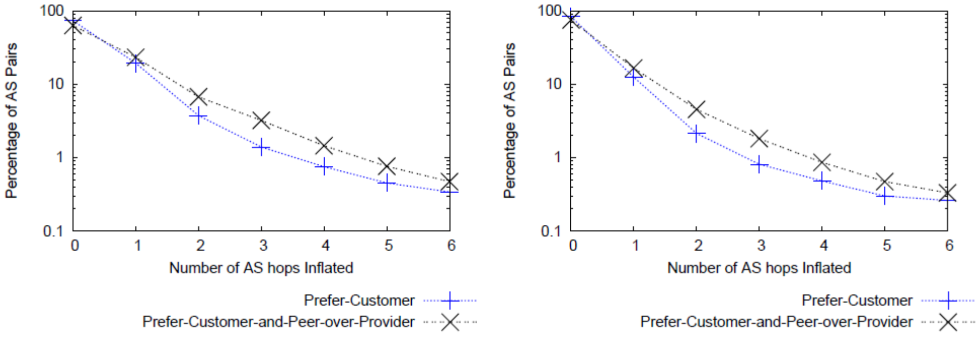


Figure 11. An Example of Path Inflations Occurring at A Transit AS (AS 6461), A Single-Homed AS (AS 1280), and A Multi-Homed AS (AS 6102)

As shown in Figure 12(a), about 27% of the AS paths derived from the Prefer-Customer policy, and 33% of the AS paths de-rived from Prefer-Customer-and-Peer-over-Provider policy can be inflated by at least one AS hop for the selected transit ASes. We observe that the Prefer-Customer-and-Peer-over-Provider routing policy tends to cause more AS path inflations than the Prefer-Customer policy does.

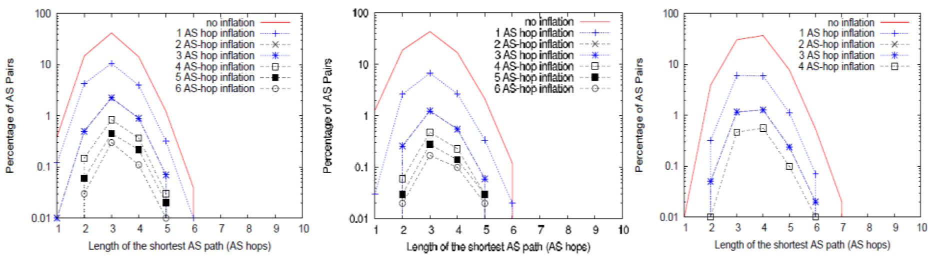


(a) Transit ASes (b) Single-homed ASes

Figure 12. AS Path Inflation Due to the Prefer-Customer and Prefer-Customer-and-Peer-Over-Provider Routing Policies

For transit ASes, as shown in Figure 13(a), we see that the AS paths derived from the Prefer-Customer routing policies can be inflated by as long as 11 AS hops while the shortest AS paths are at most 5 AS hops. Similarly, as shown in Figure 14(a), the AS paths derived from the Prefer-Customer or Prefer-Customer-and-Peer-over-Provider routing policies can be inflated by as long as 11 AS hops while the shortest AS paths are at most 5 AS hops.

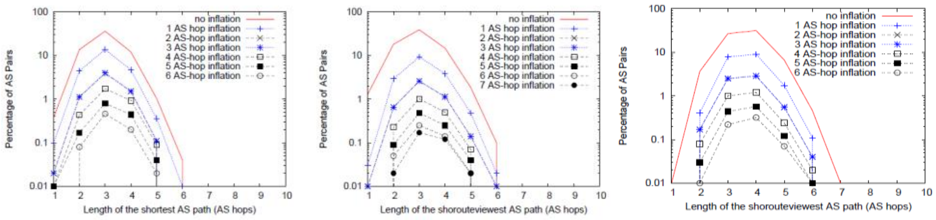
As shown in Figure 12(b), for selected single-homed ASes, about 17% of the AS paths derived from the Prefer-Customer policy can be inflated by at least one AS hop, and more than 25% of the AS paths derived from the Prefer-Customer-and-Peer-over-Provider policy can be inflated by at least one AS hop. Similar to the result from transit ASes, we observe the same fact that the Prefer-Customer-and-Peer-over-Provider routing policy tends to cause more AS path inflations.



(a) Transit ASes (b) Single-homed ASes (c) Multi-homed ASes

Figure 13. A Comparison of AS Paths Derived From the Prefer-Customer Policy and the Shortest AS Paths for All Selected AS Pairs

For the Prefer-Customer policy, as shown in Figure 13(b), we see that for single-homed ASes the AS paths derived from the policy can be inflated by as long as 11 AS hops while the shortest AS paths are at most 5 AS hops. As shown in Figure 14(b), we observe that the AS paths derived from Prefer-Customer-and-Peer-over-Provider routing policy can be inflated by as long as 12 AS hops while the shortest AS paths are at most 5 AS hops.



(a) Transit ASes (b) Single-homed ASes (c) Multi-homed ASes

Figure 14: A Comparison Of AS Paths Derived From The Prefer-Customer-And-Peer-Over-Provider Routing Policy And Shortest AS Paths For All Selected AS Pairs.

Finally, we study the path inflation occurring at multi-homed ASes. Figure 12(c) shows that around 20% of the AS paths de-rived from the Prefer-Customer policy can be inflated by at least one AS hop, and more than 30% of the AS paths derived from the Prefer-Customer-and-Peer-over-Provider policy can be inflated by at least one AS hop. Similar to the previous results, we observe the same fact that the Prefer-Customer-and-Peer-over-Provider routing policy tends to cause more AS path inflations.

From Figure 13(c), for multi-homed ASes, we see that the AS paths derived from the Prefer-Customer policy can be inflated by as long as 10 AS hops while the shortest AS paths are at most 6 AS hops. From Figure 14(c), we observe that the AS paths de-rived from Prefer-Customer-and-Peer-over-Provider policy can be inflated by as long as 12 AS hops while the shortest AS paths are at most 6 AS hops in both years.

We summarize our measurement results as follows:

- No-valley routing policy causes the least number of AS path inflation. On the contrary, Prefer-Customer-and-Peer-over-Provider policy could cause the largest number of AS path inflation among all the three routing policies.
- Single-homed stub ASes experience more path inflations than transit ASes and multi-homed ASes.
- The shortest AS paths with 3 AS hops experience more path inflations than other shortest AS paths.

3.5. Accuracy of Inferred Policy-conforming AS Paths

In this section, we investigate the accuracy of the inferred policy-conforming AS paths. For a source and destination AS pair, we compare the length of the inferred AS paths with the length of the actual AS path set. Note that there may be more than one AS path between the AS pair. We check whether the inferred AS path has the same path length with one of the actual paths. We represent the result by longer, shorter or equal match.

As shown in Figure 15 and Figure 16, for 12 tier-1 ASes, more than 70% of the inferred AS paths has the same AS path length with the actual AS paths. For the selected tier-2 ASes, the accuracy drops to about 65%. For the selected tier-3 ASes, the accuracy drops to about 50%.

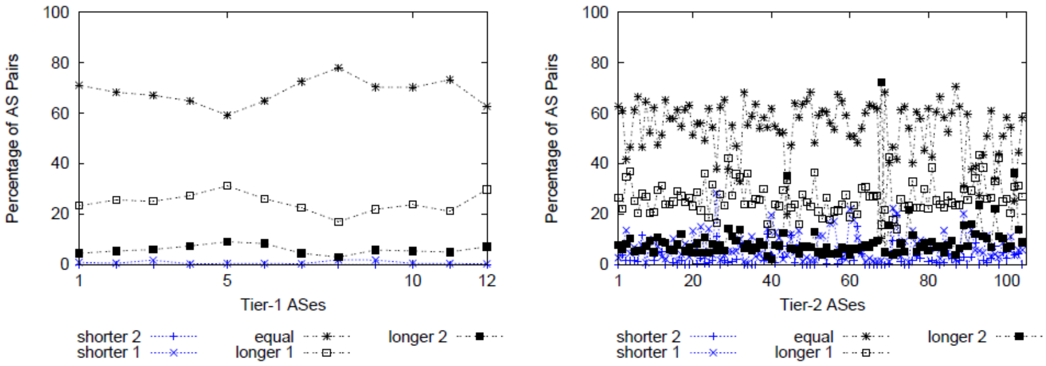
3.6. Path Inflation Changes

We are interested in understanding the AS path inflation changes. For example, as the Internet is becoming more and more condensed, we want to know whether this can help us to solve the AS path inflation problem. To answer this question, we compare the AS path inflation that we derive in 2003 and 2013 data sets. We use routing tables from the RouteViews and the RIPE RIS in June 1, 2003 to construct an AS graph respectively. First, we search the common ASes from both graphs. And then, we pick a source and destination AS from those ASes, and examine the path inflation between the AS pair.

Finally, we compare the path inflation results from the two years. In our data set, there are 9,006 common ASes in 2013 AS graph and the AS graph in 2003.

For a given AS pair, the comparison result could be:

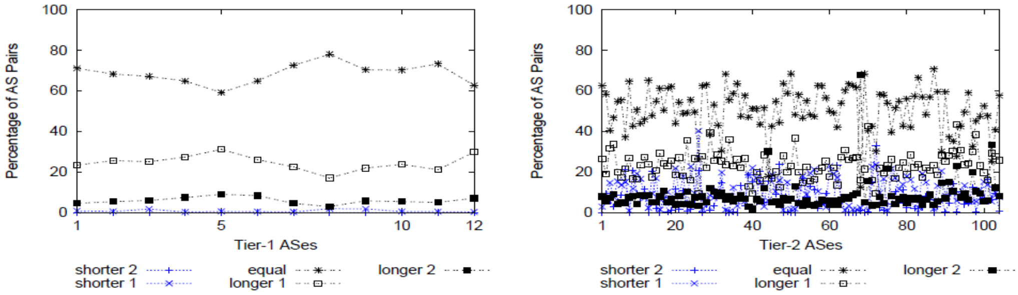
- No Path Inflation: there is no path inflation for the AS pair in the two years.
- Unchanged Path Inflation: the path inflation for the AS pair is not changed in the two years.
- Increased Path Inflation: the path inflation for the AS pair is increased in 2013.
- Decreased Path Inflation: the path inflation for the AS pair is decreased in 2013.



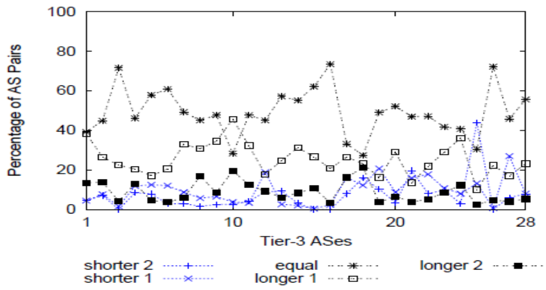
(a) Tier-1 (b) Tier-2

Figure 15: Comparison Of AS Paths Derived By Prefer-Customer Policy With The Actual AS Paths From The BGP Monitoring Peers That Are Peering With Routeview And RIPE.

Table 1 shows the comparison results. Because the Prefer-Customer and Prefer-Customer-and-Peer-over-Provider routing policies cause more path inflation than the No-Valley policy, we only show the path inflations due to the two policies. We find that about 60% of the AS pairs do not have any path inflation, which is consistent with our previous result. Among 40% of AS pairs that have at least one AS hop inflation, we find that a very small number (about 5%) of AS paths have the same inflation.



(a) Tier-1 (b) Tier-2



(c) Tier-3

Figure 16: Comparison Of AS Paths Derived By Prefer-Customer-And-Prefer- Figure 16: Peer-Over-Provider Policy With Real AS Paths From The BGP Monitoring Peers That Are Peering With Routeview And RIPE.

For those AS pairs with an increased or decreased path inflation, we try to understand the underlying reason for the change. If an AS pair has an increased path inflation, the change could be caused by 1) the shortest path is shorter in 2013 than in 2003, or 2) the inferred policy-conforming path is longer in 2013 than in 2003. Similarly, if an AS pair has a decreased path inflation, the change could be caused by 1) the shortest path is longer in 2013 than in 2003, or 2) the inferred policy-conforming path is shorter in 2013 than in 2003.

Table 1: The Comparison Of AS Path Inflation In 2003 And 2013.

Categories	Policies	
	Pref-Cust	Pref-Cust-and-Peer-over-Provider
No path inflation	67.86%	59.52%
Unchanged path inflation	3.03%	4.8%
Increased path inflation	17.44%	19.91%
due to longer policy-conforming path	61.29%	63.61%
due to shorter shortest path	35.36%	30.33%
due to longer policy-conforming path and shorter shortest path	3.35%	6.06%
Decreased path inflation	11.67%	15.77%
due to shorter policy-conforming path	84.88%	85.39%
due to longer shortest path	11.17%	10.09%
due to shorter policy-conforming path and longer shortest path	3.95%	4.52%

For those AS pairs with increased path inflation, we find that more than 50% of the increased inflations is due to longer policy-conforming paths in 2013, while only less than 30% of increased inflation is due to shorter shortest AS paths in 2013. For those AS pairs with reduced path inflation, we find that the majority of the decreased inflations (more that 85%) is due to longer policy-conforming paths in 2013, while only about 10% of increased inflation is due to shorter shortest AS paths in 2013. This observation also implies that the routing policy plays a big role in AS path inflation, which is consistent with our previous results.

4. Path Inflation at Google and Comcast

According to recent work [28, 29], content providers, such as Google, and cable Internet service providers, such as Comcast have changed their inter-connection strategies, and built their own global backbones. For example, Google moves the majority of its video and search traffic away from transit providers to its own backbone infrastructure and directly connects with consumer networks. As a result, the majority of today's inter-domain traffic flows directly between large content providers, data center/CDNs, and consumer networks [28]. In this section, we study two cases: one content provider, Google, and one cable Internet service provider, Comcast. We focus on the AS level paths to reach the two providers.

We obtain a set of AS numbers that belong to Google via a private communication. Google has 15 AS numbers, but not all of them are shown in BGP tables from RouteView and RIPE. Only 9 AS numbers are shown in our data set. In 2013, there are 264 ASes that are directly peering with Google. At the same time, we obtain a set of AS numbers that belongs to Comcast from the website (http://as.robtex.com/as15169.html). In 2013, Comcast has 48 ASes, and 1556 ASes are directly connected with those ASes.

Based on the AS graph we build before, we compute the shortest AS path and policy-conforming paths between any AS in the graph and the nearest AS of Google or Comcast. Specifically, we first compute the shortest AS path and the policy-conforming path from any AS in the graph to each AS of Google or Comcast. And then, we select the shortest path as the required AS path.

Figure 17(a) shows the distribution of the shortest AS path and two policy-conforming paths to reach Google. We observe only 0.34% of the shortest AS paths having one AS hop, and 46.10% and 48.32% of them having two and three AS hops respectively. Thus, the majority of the shortest AS paths consist of two or three AS hops. On the contrary, the average AS path length in the Internet is about 3.9 hops [9]. At the same time, we observe that the No-Valley paths have similar distribution as the shortest AS paths. However, Prefer-Customer and Prefer-Customer-and-Prefer-Peer-over-Provider routing policies can make the policy-conforming paths longer than no-valley paths, and more than 10% of the policy-conforming paths consist of more than four AS hops. From Figure 17(b) we find that about 98% of the No-Valley paths to reach Comcast are not inflated. That means, only 2% of No-Valley paths are inflated by one or more AS hops. However, about 12% and 15% of the AS paths derived by Prefer-Customer and Prefer-Customer-and-Prefer-Peer-over-Provider policies are inflated by one or more AS hops.

As shown in Figure 18(a), we observe 2.37% of the shortest AS paths having one AS hop, and 57.99% and 36.18% of them having two and three AS hops, respectively. Thus, about 96%the shortest AS paths have two or three AS hops. We also observe that the No-Valley paths have almost the same distribution as the shortest AS paths. However, Prefer-Customer and Prefer-Customer-and-Prefer-Peer-over-Provider routing policies can make the policy-conforming paths longer than No-Valley paths, and about 10% of the policy-conforming paths have longer than four AS hops. From Figure 18(b) we find that about 99% of the No-Valley paths are not inflated. About 8% and 12% of the AS paths derived by Prefer-Customer and Prefer-Customer-and-Prefer-Peer-over-Provider policies are inflated by one or more AS hops.

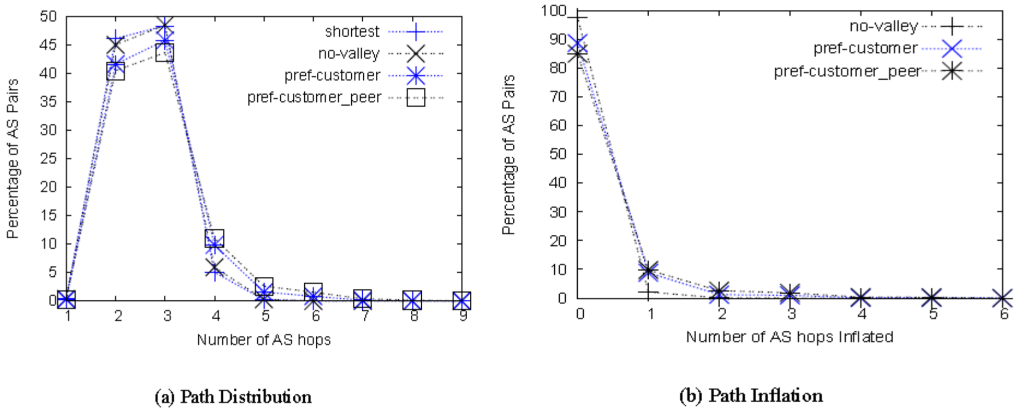
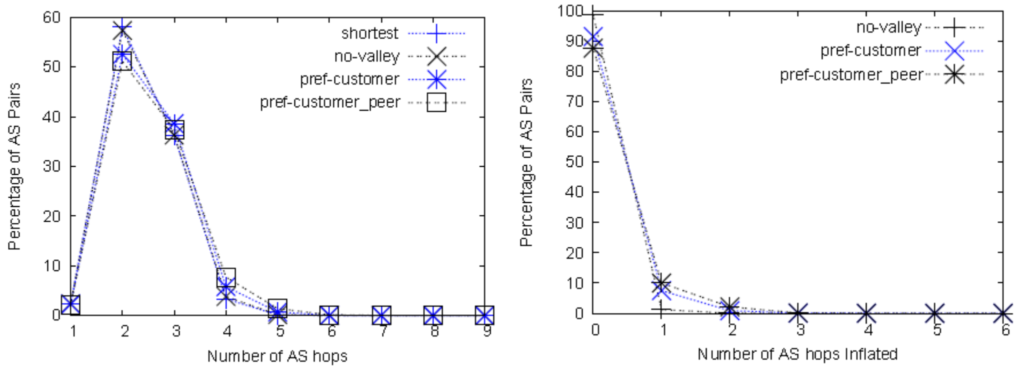


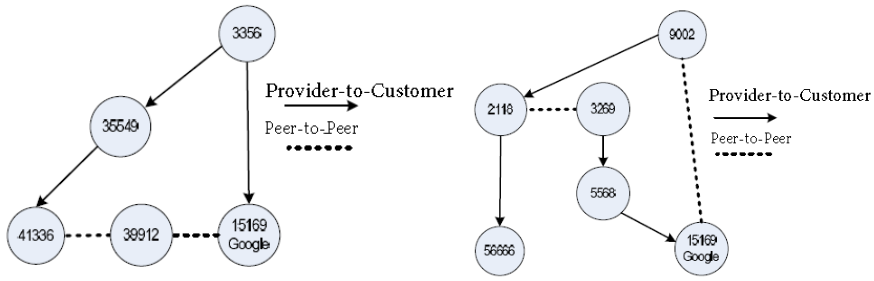
Figure 17. Path Distribution and Path Inflation at Google



(a) Path Distribution (b) Path Inflation

Figure 18. Path Distribution and Path Inflation at Comcast

We use two examples to illustrate the path inflation occurring at Google. In the first example, as shown in Figure 19(a), the shortest path from AS 41336 to one of Google's ASes (15169) is path (41336 39912 15169). But the path is an invalid/valley path because AS 41336 is a peer of AS 39912 and AS 39912 is a peer of AS 15169, which traverses two peer-to-peer links. The valid path, or no-valley path is path (41336 35549 3356 15169). In this path, AS 41336 is a customer of AS 35549, and AS 35549 and AS 15169 are the customers of AS 3356. In this example, the path from AS 41336 to Google is inflated by one AS hop.



(a) Example 1 (b) Example 2

Figure 19. Examples Of AS Path Inflations Occurring At Google

In the second example, as shown in Figure 19(b), the shortest AS path from AS 56666 to Google (AS 15169) is path (56666 2118 9002 15169), which is a no-valley path. In this example, AS 2118 has two paths: path (2118 9002 15169), which is learned from its provider AS 9002, and path (2118 3269 5568 15169), which is learned from its peer AS 3269. If AS 2118 uses the Prefer-Customer-and-Prefer-peer-over-provider routing policy, it uses path (2118 3269 5568 15169), which makes the chosen path inflated by one AS hop.

5. Conclusions

We performed measurement studies on AS path length and observed that AS paths are inflated significantly by inter-domain routing policies. This leads us to systematically study the extent of AS path inflation by routing policies. We choose three typical routing policies to estimate the extent of AS path inflation for all AS pairs. We found that a significant of AS pairs choose a longer AS path than the shortest AS path. This study shows that the shortest AS path routing policies are not typical routing policies used in the current Internet, and AS path inflation is more prevalent than expected. As part of our future study, we plan to understand how the chosen AS path differs from the AS path resulting from a typical routing policy such as no-valley-and-prefer-customer routing policy. This can give us insight into the routing policies configured in the Internet and the extent of traffic engineering performed in the Internet.

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