Summary Review Documentation for

“On the Incompleteness of the AS-level Graph: a Novel Methodology for BGP Route Collector Placement”

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Reviewer #1

Summary: This paper has three parts: first, it presents an up to date characterization of the BGP visibility obtained from the three largest public sources: routeviews, RIPE, and PCH. Next, it proposes a criterion for a good monitoring infrastructure: one in which no AS is more than one provider-customer hop away from a monitor. It derives for the publicly available dataset, the minimal set of ASes that meet this coverage goal. It discusses the properties of ASes that should be monitored.

Strengths: The question of BGP monitor placement is important, hard to study, and not often examined. This paper sheds important light on this question.

Weaknesses: The paper’s results are somewhat misstated, and the ultimate output is an approximation of unknown quality.

Comments to authors: The first part of the paper is helpful but doesn’t really contain anything new. The discussion about the differences between routeviews/RIPE and PCH is helpful for folks who are using that data.

As regards Section 3, the results are presented in a strange way. The authors are solving a set-cover problem. Clearly there is no efficient algorithm to solve this problem (unless P = NP). So it is strange for the authors to discuss an "algorithm" for this problem. Rather, what they have done is apply brute-force search to one specific dataset and found that they can obtain the optimal solution for that dataset. In particular, the authors provide no guarantees that their algorithm will run in acceptable time on any other dataset. So the claims (eg in the abstract) that they have “designed a novel algorithm for selecting the optimal number of ASes” should be removed.

Further, the results are optimal only with respect to the constraint that no AS is more than one producer-consumer hop away from a monitor. This provides no guarantees on the fraction of links that will be observed using this monitor set. It is simply a heuristic that may or may not work well.

The authors have not considered the effects of missing p2c links in their dataset. It would seem that the optimal set remains a set cover when missing links are added (good) but is no longer optimal (bad). The authors should acknowledge this fact and discuss the limitations due to missing p2c links.

Nonetheless, the notion of a p2c distance is a valuable one, and the heuristic of being at most one p2c link from a monitor seems like a good idea, and one that deserves more discussion in the community. It is important to take into account the nature of BGP relationships when analyzing the AS graph and the authors have done that. The procedure that the authors used is valuable as well.

Unfortunately, the results show that around 50% of non-stub ASes need to be instrumented in order to achieve the 1-p2c distance requirement. This negative result is helpful nonetheless for pointing out where BGP monitoring should be going.

Reviewer #2

Summary: This paper attempts to gauge the completeness in AS topology coverage of the best publicly available BGP data repositories, and comes up with a methodology for choose new (AS) vantage points to improve coverage. It provides extensive quantitative analysis of the 3 most well-known repositories (RV, RPLE, PCH) in terms of how much AS topology they capture.

Strengths: The quantitative analysis provided in the paper of the three different repositories has not yet been published, to my knowledge, and is important to the community.

It confirms some previous findings about these repositories to my knowledge, and is important to the community.

Among the well-known findings they confirm are that:

1. “Full feeders” to these routing data repository projects are mostly large national/international ASes, including most Tier 1 networks, and that the view represented by these feeders is not necessarily an accurate representation of the entire Internet topology. In particular, the feeders ASes at the top of the routing hierarchy will not see most peer links. http://www.caida.org/publications/papers/2011/bgp-traceroute_report/

2. Many BGP feeders treat the RV/RIPE collectors as peers instead of customers. (same reference)

3. Most links discovered by PCH are already seen at RV/RIPE, because ASes seem to treat PCH as peer.

4. Looking at the connectivity seen from a BGP feeder X directly, vs. the connectivity of X seen from all other BGP feeders can be used to classify feeders as partial or full. (also done in “Measuring the Evolution of Internet Peering Agreements”, IFIP Networking 2012.)

Although not immediately (or perhaps ever) relevant given the opt-in nature of these data repositories, it is useful to have an analysis of how far the current systems are from “optimal” in terms of coverage of contributing feeds.
The paper looks at causes of why current route collectors fail to capture a large fraction of the AS-topology and they propose an approach to determine how route collectors should be deployed to improve on coverage.

**Strengths:** The paper addresses an important problem and develops an interesting technique to improve the problem in a systematic way.

**Weaknesses:** The paper is incredibly hard to read.

**Comments to authors:** I found this paper very interesting, both in terms of the observations it makes on the current status of AS-level graph construction and in the form of the algorithm and its application in the second half of the paper. Unfortunately, the paper is very difficult to read, so a bunch of (possible important) points were not clear at all. There are problems with both the English language (e.g. choice of words and sentence structure) that result in the reader need to guess. Another problem is long sections without a clear structure.

Section 2 needs some structure (e.g. subsections) to make it easier to follow the discussion and to emphasize the main points.

Section 3, first paragraph: this is a long paragraph and it is not clear what the take away point is.

Section 3.2, first paragraph: again a long paragraph that lacks structure. You need to be more explicit about policies you are concerned with in long paths (I assume it is the use of peering links). The sense I also get that you would prefer route collectors lower in the hierarchy, but you don’t quite say that. The description of the algorithm is impossible to follow and the idea that you can obtain exact solutions by reducing the size is mysterious.

Section 3.2: I was not clear on the role of P U I U R (end of the section). Explaining this clearly is important given its role in the evaluation.

The discussion of Figure 8 does not provide a lot of intuition. It mostly reports what is in the graphs, but it does not discuss why you have these results.

The bottom line seems to be that you need to instrument 50% of the non-stub ASes. This is not the answer I would have hoped for the any specific result is a contribution.

**Reviewer #4**

**Summary:** This paper studies on the coverage of BGP collectors. The paper first analyzes 3 well-known publicly available BGP collectors (RouteViews, RIPE RIS and PCH), and investigates the causes of its incompleteness. Then, the paper proposes an algorithm to select ASes as BGP feeders in order to maximize the coverage. Finally, the paper compares the ideal sets of BGP feeders against the current BGP feeders.

**Strengths:** The paper quantifies the incompleteness of the coverage of the existing BGP collectors based on p2c relationship. Although it has been well understood that the current BGP collectors do not cover local peering connections well, it was difficult to quantify the coverage. In particular, the results underline the importance of having full-feeders from lower-levels of the p2c hierarchy.

**Weaknesses:** Although the paper shows a promising direction towards quantifying the coverage of BGP feeders, the coverage is not fully quantified by the proposed methods.

The ideal solution of adding 4 thousand full-feeders from lower-levels of the p2c hierarchy is not practical.

**Comments to authors:** This paper tackles the important and challenging problem to quantify the coverage of BGP collectors, and provides an important step towards this goal. I find the proposed p2c-distance based approach interesting and promising. The first half of the paper provides a good summary of the limitations in using AS topology provided by the current BGP collectors.

However, I am not fully convinced that the coverage of BGP feeders is fully quantified by the proposed methods.

Firstly, it is not shown that how well the proposed p2c-distance captures the real coverage of local peering connections. Is it pos-
sible to infer the coverage against p2c-distance using large-scale traceroute data (e.g., from the DIMES project)?

Secondly, the proposed feeder placement problem is not fully justified. The proposed method sets the fixed maximum number of p2c-distance, and tries to find the minimum covering set. However, there are other approaches such as fixing the number of feeders and minimizing the total p2c-distances. I’d like to see discussions on different approaches for the feeder placement problem.

The authors claim that the closest work [11] heavily underestimates the required BGP feeders, but they do not provide enough justification for the claim. It seems to me that the proposed method aiming for full coverage overestimates the required BGP feeders. So, I’d like to see fair and detailed comparison against [11].

As suggested in the conclusion, increasing a significant number of BGP feeders is extremely hard in practice so that a more practical approach is to use traceroute data to infer missing peering connections. However, the use of traceroute data weakens the contribution of the paper as the coverage of traceroute paths becomes more important than that of BGP feeders.

Reviewer #5

Summary: The paper builds a methodology for selecting ASes from which projects like RouteViews should seek to get additional BGP feeds. The objective is to select a minimum set of ASes that will best cover the AS topology. The paper starts with a characterization of the present BGP feeds for RouteViews, RIPE, and PCH. The authors note that PCH although it has many more feeds than RouteView/RIPE, it does not add much to the completeness of the AS topology. The paper then formalizes the problem of selecting BGP feeds as the minimum set coverage problem and provides an approximate solution. It then shows that a large fraction of the present feeds are not in the optimal solution and reports how many additional BGP feeds should be added to the current infrastructure to improve the completeness of the AS topology. The paper concludes with a prioritized list of ASes from which BGP collector should aim to get feeds from. Overall, I liked the paper. It provides novel insights on how many feeds are needed (and where to place them) to fully capture the AS topology of the Internet. I only had minor complains about some claims and the structure of the paper, which can be fixed.

Strengths: The paper formalizes and solves the problem of selecting additional BGP feeds for improving the completeness of AS topologies. Based on this, it provides a prioritized list of ASes from which RouteViews/RIPE should seek to get feeds from.

The paper provides a geographical analysis of the incompleteness of the AS topology in different continents. It shows that we know very little about the topology of Africa.

The paper provides an interesting classification of the feeds of RouteViews, RIPE, and PCH. It shows how many feeds are full, partial, and minor. It also shows that a large fraction of the present feeds are not in the optimal solution.

The paper shows that roughly 9K (based on Table 6) feeds are needed to fully capture the AS topology.

Weaknesses: The paper shows that new feeds are primarily needed in small multihomed ASes that establish multiple connections towards regional providers. This is not surprising.

The paper is easy to read. However, it develops very slowly. The key ideas of the paper are first presented only in pages 7 and 8, which is way too late. In addition, some of the interesting results of the paper are hidden in the text, without even been mentioned in the introduction. I also found the introduction a bit too long. It might be a good idea to split it in two parts: introduction & background.

The paper does not validate its main assumption: a feed in the customer cone of an AS captures the connectivity of the AS. Having said that, I find this assumption reasonable.

Comments to authors: The main claim of the analysis of section 3 is wrong. In particular, the paper claims that a route collector can discover the *full connectivity* of a given AS iff the collector gets a feed from within the customer cone of the AS. This is not true. Even if the collector receives a full feed as a direct client of the AS, it may still not see the full connectivity of the AS. This is simply because BGP is a policy-based protocol (and not a shortest path protocol) and anything can happen, including selecting a longer path to reach a neighbor. Even worse, if the collector is further down in the customer cone of an AS it will miss further links because intermediate nodes may select alternative path to reach the neighbors of the AS. Fortunately, this claim is not essential for the rest of the analysis. The authors need to relax it or explicitly say its an assumption of their algorithm.

The paper says in the bottom of page 5 that *each AS* selects and announces only the best AS path. This is wrong. *Each BGP router* selects and announces only its best AS path. BGP router decisions across an AS need not be consistent and an AS may therefore announce multiple AS paths.

I liked the observation that you find only 7% of the stub ASes participating in IXPs. You also mention that you derived this figure by manually extracting the lists of participants in 190 IXPs! which is impressive. You only mention this in a footnote. You should provide more details about the used data.

Besides, there are some similar interesting novel observations scattered throughout the paper. It would be useful to summarize such figures in the introduction too. Now the reader has to carefully read the entire paper to understand your work. The introduction does not reflect some of the interesting findings you report further on.

The paper shows that only a small percentage (roughly 30%) of the current BGP feeders are placed in the optimal solution. However, since an optimal solution is not unique, do these numbers change for different solutions? The paper should clarify this.

Figure 2(b) is almost identical to 2(a). It does not seen to add something to the paper. Besides, how are subnets defined in Figure 2(b)?

I was not sure how the authors define a stub. Are ASes C and D in Figure 4 stubs? Please try to make this more clear.

The many missing p2p links of AS topologies derived from BGP data was first highlighted in the paper “AS Relationships: Inference and Validation” CCR 2007 based on private data from several ASes. The authors seem not to be aware of this paper.

In Table 5 it seems essential to also know how many ASes are in a distance of infinity.

In Table 7 the paper also reports stubs. However, earlier on it dismissed stubs from candidate feeders, which is confusing.
I liked the observation that candidate feeders returned by the algorithm of the paper do not typically participate in IXPs. The paper should provide more details about this. What is the specific number?

Figure 5 is interesting, but it is only minimally commented in the text. It seems, for example, that some full feeds miss part of their direct adjacencies. The paper should describe this figure more.

Response from the Authors

First of all we would like to thank the reviewers for their constructive comments. We found extremely interesting the comments about traceroute (Reviewer 4). We think that traceroute and BGP data should be complementary. We are currently working to extend this work with the analysis of the available traceroute projects to provide a full view of the current Internet measurement tools. We agree with Reviewer 1 about the lack of a novel algorithm to solve a MSC problem in this paper. Rather than that, we proposed a methodology to quantify the amount of incompleteness of the current RC infrastructure, proposing a MSC problem adapted on the AS-level graph with p2c-distances, and showing how to solve it by applying mathematical techniques. To the best of our knowledge, this is the first time that these techniques are used in this context.

We also agree with Reviewer 5 that being in the customer cone of an AS is a necessary but not sufficient condition to reveal its full connectivity. In fact, it is still possible that some of its connectivity is lost due to BGP decision process filtering: minimizing the distance (i.e. the number of BGP decision processes) of the feeders from the RCs minimizes such losses (Reviewer 2). All the above points are better explained in the revised version of the paper. We also stressed out that the methodology proposed extracts an upper bound of the real number of feeders needed, that is the optimal solution of the problem given the current set of BGP feeders. In fact, even the introduction of a single feeder may lead to a change of the p2c distances, leading the starting scenario to change (Reviewer 1). Moreover, we improved the readability of the paper by correcting the English with the help of a native speaker, by giving a better structure to the paper adding subsections in section 3, 4 and 5 and by dividing Introduction from the Related work. We also added some of the missing related works. However, we disagree with the little practical relevance of our work (Reviewer 2 and 3). It may be unfeasible to connect 4k ASes to the current RCs only relying on their volunteer opt-in infrastructure, but we believe that an infrastructure offering services in change of BGP data may be useful to improve this situation and that such data would be of key importance.