You Can't Handle the Lie: Next-Hop Verification in BGP

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Abstract

This paper presents a new protocol called *Next-Hop Verification*, which that reduces the set of contexts in which other autonomous systems are incentivized to lie while participating in BGP. The protocol works by sharing information about BGP path announcements between different ASs, using the existing structure of the network, and checking those path announcements against the true flow of traffic in the data plane. We discuss the advantages and disadvantages of this new approach, and compare its effectiveness to that of previously considered verification techniques.

1 Introduction

1.1 Background and Previous Work

Routing on the Internet involves many distinct Autonomous Systems (AS's), each with its own data sources, destinations, and links; as well as its own preferences over how traffic is routed. An AS may prefer that the traffic it sends and receives be sent over the shortest path, in order to decrease latency; or it may prefer to send its traffic through or avoiding specific other AS's for economic incentives, due to contracts between AS's about routing costs; or it may prefer to avoid certain other AS's, if it is concerned about malicious activity. In the other direction, an AS may also prefer to attract or deter traffic from certain other AS's, again for economic incentives or perhaps even to spy on certain traffic.

These AS's typically use the Border Gateway Protocol (BGP) to announce routes to neighbors and learn routes from neighbors in the control plane, and to then choose how to actually route traffic in the data plane. However, there is no way for BGP to enforce the requirement that an AS route traffic in a way that matches its announcements. Thus, due to all of the various (often conflicting) preferences that AS's have over how traffic is routed, these AS's can often have incentives to lie in the control plane about what they will actually do in the data plane, in order to influence how other AS's behave.

To counteract this, *verification protocols* have been developed which run alongside or alter BGP in order to prevent lying. Unfortunately, directly verifying the routes a packet takes in the data plane requires cryptographic signatures on every packet, as in [PS03]. This huge overhead makes full data-plane verification impractical. Instead, previous work has searched for control plane protocols which still manage to prevent or discourage certain types of lies.

Much work has been done on analyzing BGP verification protocols through game-theoretic models. [LSZ08] shows that in a general set of contexts, a form of verification called *path verification*[1] ensures that no AS or group of AS's can get strictly preferred routes for its traffic by telling lies.

However, lying can potentially give other benefits beyond getting better routes for your own traffic. [GHJ+08] analyzes BGP games in which agent's utility may depend on attracting traffic from other AS's. In this scenario, even using path verification does not suffice to disincentivize lying. They introduce another form of verification called *loop verification*, which is simpler but weaker, and describe conditions under which path or loop verification do disincentivize lying. However, they admit that many of these conditions are unreasonably strong, such as requiring that AS's always announce either all paths they are aware of or none at all to all of their neighbors.

Another proposal for detecting BGP lies—or more generally BGP faults—is NetReview [HARD09]. When using NetReview, AS's record and publish all their BGP messages in tamper-evident logs, and other AS's are able to audit these logs to check whether there are any faults. However, actually detecting the faults requires regularly auditing the entirety of every AS's logs which is nontrivial. In addition, NetReview is purely in the control plane, so additional work needs to be done if we are concerned that AS's may route in the data plane differently than what they announced in the control plane. Next-hop verification addresses both of these concerns by being relatively simpler, and by incorporating information from the data plane.

There is also much discussion of convergence in BGP. [LSZ08] argues that if we assume that the network infrastructure is not changing over time and that each AS makes BGP announcements based solely on a ranking of paths that is also constant over time, then subject to a condition called *No Dispute Wheels* the network will converge to a stable set of routes. In more general contexts though, convergence becomes very hard to reason about. Because of this complexity and the fact that in practice convergence does occur, in this paper we choose to focus on what happens after convergence. We show that if the network were to converge to a state that depends on lies, we would then be able to catch the lies and shame the liar. As a result, it should not be beneficial to lie in a way that leads to that state.

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1.2 Our contributions

Given the difficulty of preventing lies in BGP, we would at least like to be able to *detect* lies when they are told. The initial observation of this work is that there will always be at least one AS that knows what each other AS is truly doing, namely the one that directly receives traffic from it in the data plane. As a result, if AS's are willing to collaborate then there is information that can be used to detect the existence of lies, without requiring full data-plane verification. Put another way, we can just monitor each AS, rather than every packet. Based on this observation, we present a new protocol called *next-hop verification* and show that it effectively prevents lies in certain scenarios.

As with previous practical verification protocols, next-hop verification protocol runs in the control plane. However, it also uses information sampled from the data plane in order to aid verification. Specifically, it requires AS's to keep track of which of its neighbors forward traffic towards it for different destinations. Given that agents have this information, next-hop verification gives an effective way for agents to distribute queries and fact-checking using the existing structure of the network and no encryption.

We find that next-hop verification allows us to catch lies assuming there are is no traffic attraction among preferences. In this regard, next-hop verification is similar in effectiveness to path

[1] In the original paper they refer to it as route verification.

verification. In the context where preferences involve traffic attraction, we are able to significantly weaken the assumptions which [GHJ+08] needed on the preferences of AS's. In this sense, next-hop verification is sometimes more powerful than path verification (although there do exist cases where path verification will prevent a lie that next-hop verification cannot). Additionally, we find that next-hop verification is strictly more powerful than loop verification, that is, every lying situation detected by loop verification will be detected by next-hop verification (though loop verification is still more lightweight). In general, we attempt to embark on a similar program to that of [GHJ+08], experimenting with various settings and seeing where next-hop verification leads to good incentive properties.

Our general analysis of next-hop verification does however use the strong assumption that there is only a single lying agent. We also for simplicity and power focus on the situation in which everyone else participates fully. That said, the protocol would still provide some value even with only partial participation, and we will discuss this in Section 5.

I've not thought about collusion-proofness for next-hop. Unless we do, I'd significantly shorten this paragraph

1.3 Organization

In the rest of Section 1 we discuss existing work, and we briefly outline our results and their limitations. Section 2 informally presents the model we use. Section 3 describes the next-hop verification protocol. Section 4 states and proves some theorems about the implications of using next-hop verification, and goes through examples of concrete scenarios to compare what would be possible with and without next-hop verification. Finally, Section 5 offers some suggestions for follow-up work and Section 6 concludes.

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2 Model Details

2.1 BGP framework

We model the network of AS's as an undirected graph, with a node for each AS and an edge between any two AS's that can directly communicate with each other without going through a third AS. We assume that the graph is a single connected component, so any AS can in theory interact with any other AS (although in practice, say if an intermediate AS intentionally drops traffic, this may not always actually be possible). As is standard in the literature, we assume there is a unique destination AS d, because routing to different destination (prefixes) is done independently in BGP.

what is this comment for?

In the BGP framework, AS's can announce the existence or removal of paths to each other. Each AS has an import policy that determines how it responds to path announcements from neighboring AS's. Specifically, the import policy determines whether the AS will update its route, given a new announcement. ((PERHAPS DISCUSS THE NOTION OF PREFERENCES AND THUS MENTION HONESTY HERE))

In this paper we ignore any concerns of storage for keeping track of all announcements from neighbors, so we assume that any newly observed path is added to a table, unless the receiving AS is already in the path. In this case it will either ignore the path announcement, or if the AS never announced the subpath containing itself it will raise an alarm that another AS has exported a false path. We also assume that on hearing an announcement, the AS can only take actions related to the full path, and not related to particular subpaths.

what is this sentence for?

It's too early to talk about look verification

what does this mean?

Each AS also has an export policy which determines how it will communicate the paths it is aware of to other AS's. Specifically, for a BGP compliant AS, the export policy determines whether or not to announce the AS's currently chosen route to a given neighbor. In realistic settings an AS may prefer not to announce its path to all neighbors (the most famous example of this being [GR01], in which for example customers will not route traffic between two of their providers). However, for a manipulative, non-BGP compliant AS, a much richer set of export policies is available. The AS can lie arbitrarily, announcing paths that it doesn't use or that don't even exist.

Finally, each AS has some preferences over how the actual traffic in the network flows. The AS's will choose a strategy, namely their import and export policies, based on these preferences.

We assume that the collection of strategies leads the network to converge to a stable solution. See [LSZ08, GHJ$^+$08, GSW02, GSW99] for examples of more formal details about proving different types of convergence and what assumptions are necessary.

maybe move the convergence paragraph from "background" to here?

Definition 1. *Suppose a BGP network G has reached a stable equilibrium. We say that an AS* $\boldsymbol{m}$ *is* ***lying*** *if the it exports a route other than that which it is using. We say that an AS is* ***honest*** *if it is not lying.*

2.2 Verification

In this section, we give an overview of some previously considered verification protocols. These will be our comparison points for next-hop verification.

Definition 2. *In a network using* ***path verification*** *it is impossible for AS's to announce that they are using paths which were not already announced to them.*

Some extensions to BGP, such as S-BGP, can enforce path verification. However, it requires additional overhead as well as universal adoption [LGS13], because every route communicated in the control plane must be cryptographically signed by every AS along that route.

Definition 3. *In a network using* ***loop verification*** *no AS will use an export policy that involves not sending a path to a neighbor specifically because that neighbor is already in the path. In addition, if an AS ever sees a path containing itself that it did not announce, it will "raise an alarm", with the idea that the offender (the first node which announced a false path) can be publicly shamed.*

Note that if instead export policies did not send paths to neighbors who are already in them, the alarming in loop verification could not always be done.

2.3 Behavioral assumptions

When agents get utility from attracting traffic, stronger verification protocols are needed to disincentivize lying. In [GHJ$^+$08], the authors consider the following classes of preferences which depend on more than just an AS's own path.

Definition 4. *An AS m cares about* ***volume attraction*** *if its utility can depend on the set of AS's that route through m.*

An AS m cares about ***generic attraction*** *if its utility can depend on the set of AS's that route through m AND on the routes these AS's take to get to m.*

Volume attraction can reflect truly malicious situations such as spying, where the manipulative agent wants to view packets for some nefarious reason. Issues like this may occasionally have huge consequences for the global routing behavior of the internet, for example, the 2010 China Telecom

BGP hijacking could've potentially served this function [DS18]. It could also simply reflect an economic incentive such as getting paid for routing more traffic.

With preferences for generic attraction, an AS m may have incentives to affect *how* other agents route through m. For example, a provider may want a customer to route directly through it in order to charge that customer more.

We briefly consider one assumption on the path preferences of AS's as well:

Definition 5. *An AS n has a **next hop policy** if its utility for a given path is a function of only the first AS along the path (i.e. the next-hop).*

3 Next-Hop Verification Protocol

We now define next-hop verification. This protocol is run on a BGP network after convergence has already occurred. Nodes communicate along existing links in the network, storing and sending next-hop queries. We assume that AS's can "raise the alarm", similar to [GHJ+08], which refers to alerting others that something is going wrong with the particular query. For our results section, we will assume that when the alarm is raised, the offending agent will be caught (for example, via the collaboration of the NANOG mailing list to detect the problem, as suggested in [GHJ+08]).

Each node maintains a queue of queries which it needs to answer. A query is denoted $Q_d(a, b)$, representing a node announcing that a uses b as its next-hop in its path to destination d. During initialization, every node n adds the query $Q_d(a, b)$ to its own queue, for every hop (a, b) on n's path to the destination d. From that point on, every round in which n acts, it runs the function RESPOND on every query $Q_d(a, b)$ waiting in its queue, then waits for more queries.

Denote the acting AS by n
function RESPOND($Q_d(a, b)$)
    if n previously responded to $Q_d(a, b)$ **then**
        return
    if $n = a$ **then**
        if n does not use b as its next hop for d **then**
            "raise the alarm"
        return
    if $n = b$ **then**
        if a does not use n as its next hop for d **then**
            "raise the alarm"
        else
            send the query $Q_d(a, b)$ to all neighbors
    else (i.e. $n \neq a, b$)
        if a uses n as its next hop for d **then**
            "raise the alarm"
        else
            send the query $Q_d(a, b)$ to all neighbors

3.1 Additional considerations

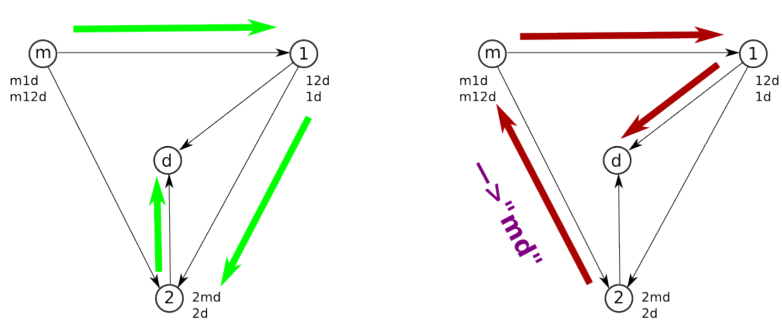
- In the case where n is responding to a query $Q_d(a, n)$, it needs to check whether a actually forwards traffic directly to n for destination d, which must be done in the data plane. Accordingly, each AS should keep a flag for each other (neighboring AS) × (dest AS) pair, representing whether the first AS ever directly sends n traffic destined for the second AS.

- In practice, maintaining the accuracy of this information in the face of the dynamic nature of routing would be difficult. However, we take this information as given. In particular, we assume that traffic is sent often enough toward the destination that the absence of traffic means that a given route is not being used. rephrase

- If a manipulator is lying about the next-hop it is personally using, it may intentionally send occasional traffic towards its announced next-hop, while sending the bulk of its traffic down the route that it genuinely prefers. We take this strategy into consideration, and our theorems hold even allowing for this. However, it means that next-hop verification cannot "confirm the hop" if $n = b$ and a uses b as its next-hop, and must instead forward the query on to its neighbors in line 13 of Respond. ((WE HAVE A CONCRETE EXAMPLE OF THIS IF THERE IS SPACE, AT LEAST FOR VOLUME ATTRACTION))

For a motivating example of next-hop verification, consider the network given in Figure 1. Here, m is able to get a preferred path to the destination by falsely announcing the path md to node 2. However, nodes 1 and d, which are both one hop away from 2, can tell that this announcement is not legitimate: d knows that m does not route directly to d, and 1 knows that m routes directly to 1 instead of d. Thus, both d and 1 will "raise the alarm" if they are compliantly running next-hop verification.

Figure 1: NonexistentPath



4 Results

Our first result formalizes the statement "in a network without traffic attraction, next-hop verification will catch all incentivized lies". Figure 1 demonstrates this theorem, as discussed above.

Theorem 1. *Let G be a stable outcome of a BGP instance without traffic attraction. Suppose there is a single manipulator m, and all other nodes honestly participate in BGP and in next-hop* *verification. If m lies in order to get a better path to d, then next-hop verification will catch that lie and shame m.*

Proof. Suppose m announces a hop (a, b) to v, where (a, c) is actually in a route from m to d for some $c \neq a$. (Note that m could send traffic to both b and c if $m = a$.) For contradiction, assume that every path from c to v includes m The route from m to d which includes (a, c) must not have loops, so it cannot include m again. If there was a path from v to d which did not contain m, then the path from c to d would give a simple path from v to c not containing m. Thus, every route from v to d includes m.

Because all non-m nodes are honest, m must get v to change its route to d in order to get a different path by lying to v. (More technically, there must exists a choice of v which picks a different path). However, v's route cannot effect m's route to d, because every route from v to d includes m, so no route of v nor any consequence of v's route can change the set of paths available to m. This contradicts the assumption that m got a better path by lying, and shows that there exists a path P from c to v not including m.

Now, because all nodes along P are participating in the next-hop protocol, the node v will ask the query $Q_d(a, b)$, which will travel along path P until c can "raise the alarm" in line 16 of RESPOND. □

The next result shows that next-hop verification is at least as powerful as loop verification:

Theorem 2. *Let G be a stable outcome of a BGP instance. Suppose there is a single manipulator m who lies in the stable outcome, and all other nodes honestly participate in BGP and in next-hop verification. Then if m would be necessarily be caught by loop verification, then m will be caught by next-hop verification.*

Proof. As shown above, an AS cannot be incentivized to lie just to get a better path: there must be traffic attraction. Suppose m attracts traffic from some node v by falsely announcing a path P from m to d. The manipulator m must announce the path P, paths containing P must spread outward through some part of the graph, and v must end up routing through P. Let the tree of agents who end up routing through P be denoted by T (in particular, $v \in T$). Note that $T \setminus \{m\}$ is connected.

Now, the only way for loop verification to guarantee to be able to catch m in this lie is if some node q in the tree T is adjacent to a node u, such that P contains the path uR, where R is a route that u did not announce. Indeed, in this case a route containing P can be announced to u by q, and u can raise the alarm for loop verification.

Let (a, b) be the first hop along R which is not actually used in the data plane. Note that $m \notin R$. If next-hop verification is used by all non-manipulator nodes, then v will ask the query $Q_d(a, b)$. This query will travel within the tree T, through q to u, and along R until it gets to a. There, agent a will "raise the alarm" in line 7 of RESPOND, and m will be caught. □

As an aside, we note that an analogue of the above theorem for path verification does not hold[2]. Combined with the extensive discussion in [GHJ$^+$08], the previous result gives us a few different situations in which next-hop verification will catch all incentivized lies. The rest of this section is dedicated to weakening the requirements for those incentive-compatibility properties to hold.

The following theorem says that next-hop verification will still catch lies in networks with volume attraction. Indeed, unlike [GHJ$^+$08] we do not need to make *any* assumptions on preferences or behavior (other than assuming *volume* attraction) to get this positive result.

[2]For an example, consider figure 2, altered by removing the link between nodes m and l. The exact same lying strategy is still available to m under next-hop verification, but this is not possible if path verification is used.

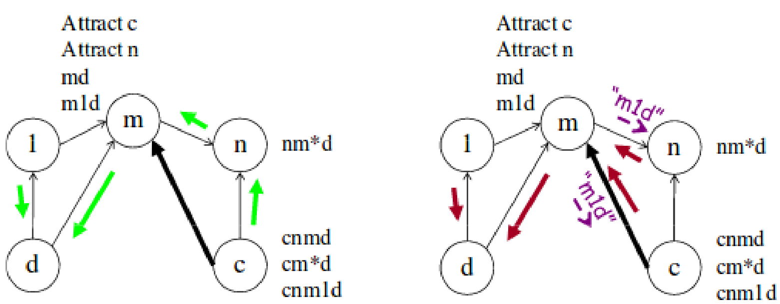
Theorem 3. *Let G be a stable outcome of a BGP instance with traffic volume attraction. Suppose there is a single manipulator m, and all other nodes honestly participate in BGP and in next-hop verification. If m lies in order to attract traffic from some node u, then next-hop verification will catch that lie and shame m.*

Proof. Suppose m did manage to attract more traffic from a victim u. Let P denotes the path u originally took to d, and let Q denote the path u takes in the manipulated outcome G. Note that $m \in Q$ but $m \notin P$. Let v denote a node that m lied to, and suppose v is told that hop (a, b) is used while (a, c) is actually used for $c \neq b$.

Because the lie told to v must effect the path chosen by u, there exists a path R from u to v not including m. Furthermore, because m uses the route S from c to d (and profits from it) we know $m \notin S$. Thus, by eliminating any possible loops from RPS, the concatenation of the three paths, we get a simple path from v to c which does not include m. Because all non-m nodes are actively and honestly running next-hop, the query $Q_d(a, b)$ will travel from v to c and c will "raise the alarm" in line 16 of RESPOND. □

However, we are not able to extend this result to generic attraction. Indeed, consider the example given by (Figure 2), from [GHJ+08]. In this network, the manipulator m wants nodes n and c to use m as their next hop for destination d, for example, because of economic considerations. The AS's who know what m is doing in the data plane are separated from the AS's m is lying to. Those victim agents cannot communicate with d and l without going through m, which can just throw their next-hop queries away to avoid being caught.

Figure 2: Bowtie



We note also that next-hop verification is able to catch the manipulator in many of the examples from [GHJ+08] (indeed, next-hop verification works for all examples except Bowtie and Disputed-Path). This may hint at many more theorems that we were unable to prove for this project. In particular, we make the following conjecture:

Conjecture 1. *Let G be a stable outcome of a BGP instance with generic traffic attraction. Suppose there is a single manipulator m, and all other nodes honestly participate in BGP and in next-hop verification. Furthermore, assume all nodes use next-hop policy in ranking their paths. If m lies in order to attract traffic from some node u, then next-hop verification will catch that lie and shame m.*

Intuitively, this should eliminate examples like Bowtie, where the victim node c was tricked into routing directly through m because his policy was not next-hop.

5 Possible future directions

I shortened several of these paragraphs. Let me know if I was too heavy-handed!

We showed in the previous section that next-hop verification has the potential to provide some major benefits for catching lies in BGP, and thus reducing or even eliminating AS's incentives to do so. However, there is still some future work that should be done before it is used in practice.

One important question is how effective the protocol can be in partial deployment or participation. In our theorems we assumed that there was only one malicious AS and that all others actively participated fully in helping to catch lies. However in practice, it maybe the case that some AS's have not deployed the necessary software and/or hardware for participation. Partial deployment and participation would still be somewhat valuable: certainly lies can still be detected if we get lucky and all the right agents participate. However, a formal analysis with strong theorems is probably difficult in the face of such partial deployment.

A related and interesting line of investigation would be into the actual incentives of mutual participation in next-hop verification. There are examples where a non-lying agent does actually get a better path through the lies of a manipulator, AND that agent's participation is needed to catch the manipulator with next-hop verification. In practice, perhaps could "fact-checking" be written into customer-provider contract agreements, e.g. providers helping customers keep track of *other* providers? In the setting of Gao-Rexford networks [GR01], it may be possible to prove strong results, such as participation in next-hop with your customers never being harmful.

check this!!!!

Perhaps the biggest practical problem with our protocol is the way it "floods" the AS graph with next-hop queries. In practice, the very minimum that would need to be added is a "time to live" field on the next-hop queries, which would prevent them from exploding over the entire AS graph.

The clear alternative to this "query flooding" is to simply encrypt the query and send it to the AS's who can answer it (just as you would normal traffic). The burden of such encryption would not be very heavy, and the resulting protocol would be a lot more practical for checking on hops which are far away from you in the AS graph. However, the ideal fact-checking protocol is one that makes only local communication, like that of path verification (with local cryptographic signatures) or the even more lightweight loop verification (which is normal BGP with a simple extra check for "did I actually announce this?"). Indeed, in examples like Figure 1, the next-hop query needs to travel only one hop before being answered. In today's very dense AS graph, that may often be the case, and with more refined knowledge of the nearby structure of the graph, an AS may be able to intelligently route its next-hop queries to get efficient answers. We view our protocol, and the theorems surrounding it, as a step towards a more refined next-hop verification capable of meeting these criterion.

the rest of this paragraph is what I meant in that mystery bullet point in the google doc

6 Conclusion

In this paper we have proposed the design of Next-Hop Verification, a protocol for catching BGP lies by using information from the control plane along with minimal data from the data plane, and by having the AS's collaborate with each other to detect these lies. We also analyzed the theoretical capabilities of the protocol, and showed that in many circumstances it is capable of catching lies that loop verification and path verification cannot catch. We believe that Next-Hop Verification's approach of sharing informationand cross-checking with the data plane is a valuable one, and that the protocol is a valuable step in working toward more secure control-plane communication.

Put a code appendix I guess?? As per piazza. At minimum we need to link to the code

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