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 reduces the set of contexts in which autonomous systems are incentivized to lie while participating in BGP. The protocol works by sharing information about BGP path announcements between different AS's, 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, focusing on cases where next-hop verification provably eliminates the incentives to lie in BGP.

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 specific other AS's for economic incentives, due to contracts 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, there are incentives to lie in the control plane about what an AS 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 control plane verification protocols through game-theoretic models. In [LSZ08], the authors show 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. In [GHJ+08], the authors analyze 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 follow an "all or nothing" export rule.

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.

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

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[2]. 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 detects 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 and answer queries about the true data plane paths used by other AS's. The distribution of queries uses the existing structure of the network and requires no encryption.

We find that assuming full compliance, 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 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 catch). 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 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.

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. 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.

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 and how the AS will update its route, when it hears new announcements. Furthermore, each AS has an export policy that determines whether it will announce its current path to a neighbor (or, if the agent is being manipulative, it could announce a path different from the one it is actually using). These import and export policies are the action space of each agent AS. Finally, each AS has some preferences over how the actual traffic in the network flows, regarding both what route it gets and how other AS's route through it. Each AS will choose a strategy, namely their import and export policies, based on these preferences.

More precisely, there are two types of actions available to each agent: installing certain routes in their forwarding table, and announcing paths to their neighbors. Let $N(i)$ denote the neighbors of AS i in the BGP graph. Formally, we could model the import policy of a node i as a function $imp_i : Path^{N(i)} \to Path$ from the (possibly empty) collection of routes currently announced as available to i, to a (possibly empty) path to use for forwarding traffic[3]. We assume that AS's have a utility function $v : Path \to \mathbb{R}$ which models their preference among the different paths to the destination. A non-strategic import policy would simply select the favorite path available to the AS at a given point in time.

The export policy could be modeled as a function $exp_i : Path \times N(i) \to Path$ from the current path i uses and a given neighbor of i to a path to announce to the neighbor (or the empty path if i does not wish to export). For a BGP compliant AS, the export policy simply amounts to choosing whether to export the path the AS currently uses (that is, we have $exp_i(j, p) = p$ or $exp_i(j, p) = []$). In realistic settings an AS may prefer not to announce its path to all neighbors, the most famous example of this being the Gao-Rexford framework [GR01], in which for example customers will not route traffic between two of their providers. The export policy may more generally be determined by the traffic attraction and repulsion preferences of the AS. 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.

[2] For the purposes of our discussion, we assume that AS's always want to avoid being caught lying, so detecting lies is the same as disincentivizing those lies.

[3] We actually allow a manipulative, non-BGP compliant agent to have a strictly larger set of available actions: the agent may forward down multiple routes

Definition 1. *Suppose a BGP network G has reached a stable equilibrium. We say that an AS* ***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.*

We assume that the collection of strategies leads the network to converge to a stable solution. In general contexts, convergence becomes very hard to reason about. Because of this complexity and the fact that in practice convergence typically does occur (at least for small local subgraphs), 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, then in some scenarios 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. See [LSZ08, GR01, GSW02, GSW99] for more formal details about proving different types of convergence and what assumptions are necessary.

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 using cryptography. 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 u ever sees a path containing uR, where u did not actually announce route R, 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 agents' export policies never sent paths to neighbors who are already in them, then loop verification could not be done. The name loop verification comes from the "routing loop" formed by announcing a path containing u to AS u.

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 import policy*** *if its choice of which path to use 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]), and its lie will be disincentivized.

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.

Whenever n acts, it runs the function RESPOND—detailed in Figure 2—on every query $Q_d(a,b)$ waiting in its queue, then waits for more queries.

After n has sent some traffic to d, it can start querying about its own route. It does this by adding the query $Q_d(a,b)$ to its own queue, for every hop (a,b) on n's path to the destination d.

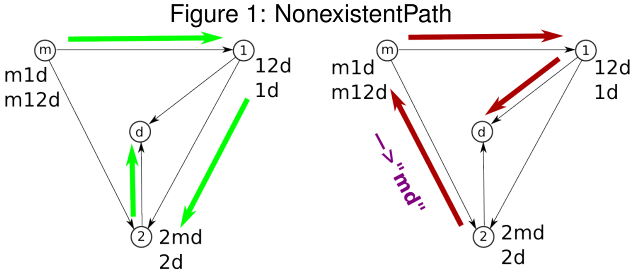
We have sketched an implementation of next-hop verification in Haskell. Visit our repository[4] to

[4] Located at github.com/ClathomasPrime/Cs561Proj/ under the bgp-fact-check/ directory.

check out the code. Of particular interest is the file src/FackCheck.hs, which implements the above RESPOND in the functions '`processMessage`' and '`factCheckAnswerQuery`'.

For a motivating example of next-hop verification, consider the network given in Figure 1 (a common example in discussions of BGP incentives [LSZ08, GHJ+08]). 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. If d, 1, and 2 are all compliantly running next-hop verification, 2 will ask both other nodes the query $Q_d(m,d)$ and both will "raise the alarm".

Figure 1: NonexistentPath



We note the following important 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) $\times$ (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. For example, AS's need to reset the flags after certain lengths of time without seeing any traffic. However, we leave the details to future work.

- We require nodes to actually send traffic before asking next-hop queries. This forces the potential manipulator to actually use at least some data-plane paths, in the hopes that it will use a false path. Intuitively, this will leave evidence of the lie, in the sense that certain AS's will know what is actually happening. More generally, we assume that enough traffic is sent such that all data-plane paths are actually observed, and that the absence of traffic means that a given route is not being used. This is a strong assumption on the traffic in the network, but in very stable networks (and for important destinations) this assumption is not too unreasonable.

- 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 if $n = b$ and a forwards traffic directly to b, then n cannot guarantee that a doesn't forward traffic elsewhere as well. Instead n must forward the query on to its neighbors in line 13 of RESPOND. Furthermore, it means we cannot rely on line 11 in any of our theorems, because if a is the manipulator it may send a small amount of "fake traffic" to b in order to "cover its tracks".

```
1: Denote the acting AS by n
2: function RESPOND(Q_d(a,b))
3:     if n previously responded to Q_d(a,b) then
4:         return
5:     if n = a then
6:         if n does not use b as its next hop for d then
7:             "raise the alarm"
8:         return
9:     if n = b then
10:        if a does not use n as its next hop for d then
11:            "raise the alarm"
12:        else
13:            send the query Q_d(a,b) to all neighbors
14:    else (i.e. n ≠ a,b)
15:        if a uses n as its next hop for d then
16:            "raise the alarm"
17:        else
18:            send the query Q_d(a,b) to all neighbors
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Figure 2: Next-hop verification pseudocode

Figure 3: FalsePositive

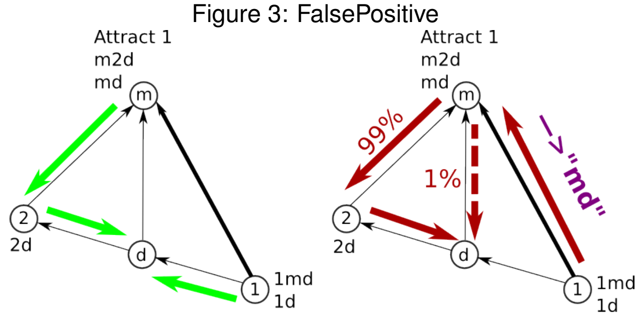


Figure 3, considered in [GHJ+08] under the name InconsistentPolicy, gives another example of next-hop verification, and also illustrates the final bullet point above. In this network, m wants to carry traffic from 1, but must lie to 1 in order for it to choose m as its next-hop. In order to obscure this lie, m can try to send a small amount of its traffic directly to d, while still using its favored path through 2 for the bulk of its traffic. Running next-hop verification, 1 will ask the query $Q_d(m,d)$ to d. Node d

will indeed observe a small amount of traffic coming from m, so it cannot raise the alarm. But it will forward the query to node 2, which will then "raise the alarm". Note that, assuming d announces the path md to m, neither path verification nor loop verification can prevent this strategic manipulation. So this is a case where next-hop verification gives us a strict advantage over existing verification protocols.

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. Assume m lies by announces a hop (a,b) to v, where (a,c) is actually in a route from m to d for some $c \neq b$. (Note that m could send traffic to both b and c if $m = a$.)

If there exists a path P from v to c that does not contain m then 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. So it is sufficient to show that such a path always exists.

Suppose for contradiction that every path from v to c includes m.[5] We will show that this is not compatible with the hypothesis that m got a better path to d by sdlying. The route from m to d which includes (a,c) must not have loops, so there exists a path P_1 from c to d not containing m. If there were a path P_2 from v to d which did not contain m, then the path P_2P_1 is from v to c and would not contain 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. □

[5] This would be a problem because m could drop next-hop queries so that its lie wouldn't be caught

The next result shows that next-hop verification is at least as effective as loop verification in disincentivizing lying in some cases:

Theorem 2. *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. Suppose that loop verification, run on the stabilized network, would catch m's lie. Then m will be caught by next-hop verification on the stabilized network.*

Proof. Suppose loop verification would detect a false path P originally announced by m. Specifically, this means that P contains a subpath uR, where R is not actually used by u, and that some node q adjacent to u installs and can announce a path containing P.

Let (a,b) be the first hop along the path uR which is not used in the data plane. When next-hop verification is run, node q will ask the query $Q_d(a,b)$, starting with u, and travelling down the path R. Note that P must be a simple path starting with m, so R cannot contain m. Thus, eventually node a will receive the query $Q_d(a,b)$, and will "raise the alarm" in line 7 of RESPOND.

□

Note that an analogue of the above theorem for path verification does not hold[6]. In practice, it is reasonable to run loop verification alongside next-hop verification, because loop verification is very lightweight[7]. Combined with the extensive discussion in [GHJ+08] about the capabilities of loop verification, 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.

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 would have otherwise taken to d. Note that by assumption $m \notin P$. Let v denote

[6] For an example, consider figure 4, 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.

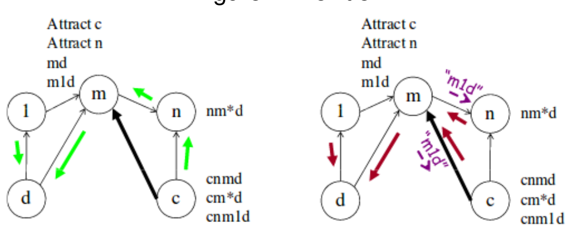
[7] It even makes the above proof more efficient: the query doesn't have to travel down the path R, it can be immediately answered at u.

a node that m lied to that affected u's route, 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 affects the path chosen by u, there must exist a path R from u to v not including m (if not, the lie could only affect u by going back through m, in which case v did not have any effect). Furthermore, because m uses some 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 4, taken directly 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 4: Bowtie



We note also that next-hop verification is able to catch the manipulator in many of the other examples from [GHJ+08] (indeed, next-hop verification works for all examples except Bowtie and DisputedPath). This may hint at many more theorems that we were unable to prove for this project. For example, 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 import 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 its import policy was not next-hop.

5 Possible future directions

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 ASs' 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. It may also be the case that some AS's choose not to participate or to only share a limited subset of the information they have, even if they are not themselves malicious, lying agents. Partial deployment and participation would still be somewhat valuable though; 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 actually gets a preferred outcome through the lies of a manipulator, AND that agent's participation is needed to catch the manipulator with next-hop verification. In practice, perhaps this "fact-checking" could 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.

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, in the same way that one would send normal traffic. The burden of such encryption would not be very heavy, and the resulting protocol would be more practical for checking on hops which are far away from you in the AS graph. However, an important aspect of our protocol is the ability for AS's that are involved in the actual route but not the fake route to raise the alarm. In addition, it seems ideal for a fact-checking protocol to make use of local information, like path verification (with local cryptographic signatures) or loop verification. 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 criteria.

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.

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