APVAS: Reducing Memory Size of AS_PATH Validation by Using Aggregate Signatures

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Abstract—The BGPsec protocol, which is an extension of the border gateway protocol (BGP), uses digital signatures to guarantee the validity of routing information. However, BGPsec’s use of digital signatures in routing information causes a lack of memory in BGP routers and therefore creates a gaping security hole in today’s Internet. This problem hinders the practical realization and implementation of BGPsec. In this paper, we present APVAS (AS path validation based on aggregate signatures), a new validation method that reduces memory consumption of BGPsec when validating paths in routing information. To do this, APVAS relies on a novel aggregate signature scheme that compresses individually generated signatures into a single signature in two ways, i.e., in sequential and interactive fashions. Furthermore, we implement a prototype of APVAS on BIRD Internet Routing Daemon and demonstrate its efficiency on actual BGP connections. Our results show that APVAS can reduce memory consumption by 80% in comparison with the conventional BGPsec.

Index Terms—BGPsec, Path Validation, Aggregate Signatures, Internet Routing, Memory Size

I. INTRODUCTION

A. Backgrounds

The Border Gateway Protocol (BGP) [1] enables networks, such as an Internet service provider (ISP), to exchange routing information in the level of autonomous system (AS) by assigning a unique number to each AS. BGP is also the primary routing protocol used in the backbone of the Internet. However, BGP does not verify the validity of routing information being exchanged, and thus an AS always registers routing information received from other ASes as valid even if an adversary manipulates the routing information. This fundamental flaw in BGP has caused many incidents that resulted in heavy and serious damages, e.g., Youtube hijacking [2] and Ethereum hijacking [3]. According to some measurement results [4], such a hijack happens about four times a day on average. Therefore, guaranteeing the validity of routing information in BGP is an urgent and significant issue.

To tackle the aforementioned issue, technologies that guarantee the security of BGP in a cryptographic fashion have attracted attention. Loosely speaking, these technologies aim to verify the validity of routing information via generation and verification of digital signatures in the routing information. Specifically, signatures can be used in two ways, namely, route origin validation that only allows advertisements for an IP prefix by the legitimate AS as a prefix owner and path validation that guarantees all members of an AS path which is a connection of ASes from a source to a destination. Route origin validation is almost consummative by virtue of the practical realizations of RPKI [5] and ROA [6], [7] as related protocols. In contrast, path validation has no clear practical realization even though it is instantiated by BGPsec [8] because its use of digital signatures significantly increases the memory consumption of BGP routers. For instance, according to a current estimation [22], a BGPsec is required to have memory size of several tens of gigabytes. The issue related to the memory size is known as the memory size problem. Moreover, BGPsec lacks experimental evaluations and thus a precise evaluation of the memory size problem remains incomplete.

BGP hijacking has also given rise to hijacking of cryptocurrencies [9], [10], such as Bitcoin, as a new aspect of cybercrime. A recent finding has shown that BGP hijacking [11] can only be prevented by the use of BGPsec. Therefore, an essential issue in BGP security can be solved by making BGPsec practical, i.e., by reducing memory consumption and solving the memory size problem.

B. Contribution

In this paper, we present a new path validation protocol named APVAS (AS path validation based on aggregate signatures), which utilizes aggregate signatures [12] to combine individual signatures into a single short signature and solve the memory size problem. Moreover, we implement a prototype of APVAS on a router daemon software. This is a first attempt to measure memory size by the use of state-of-the-art cryptography in actual devices. In our experimental environment, APVAS can reduce memory consumption by 80% compared to the conventional BGPsec. We believe that APVAS will become an innovative solution to BGPsec.

This paper presents two technical contributions. The first contribution is the proposal of a novel aggregate signature scheme named bimodal aggregate signatures. Aggregate signatures are expected be applicable to BGPsec in cryptographic theory, but the algebraic structures of aggregate signatures in early literature are unsuitable for the current specifications of BGPsec. More precisely, when the original aggregate signatures [12], [23] are trivially deployed in BGPsec, either the capability for signature aggregation or security will be lost. In contrast, APVAS can decrease the memory consumption as well as keep the security of BGPsec by the use of bimodal aggregate signatures (See Section IV for details).
The second contribution is the implementation of a prototype of APVAS by extending BIRD Internet Routing Daemon (BIRD)\(^1\), which is a software that virtualizes a BGP router. The lack of experimental evaluation described in the previous subsection is caused by the lack of evaluation tools for BGPsec. In contrast, we succeeded in measuring the performance of APVAS in an actual environment by leveraging BIRD. Although our experiment was conducted on a linear network in a simple fashion, as far as we are aware this is the first time that aggregate signatures are evaluated in an actual environment. Moreover, by extending our prototype, we can potentially evaluate protocols in future works (See Section VI for details). We plan to release the prototype of APVAS to encourage development of BGPsec and future works.

II. RELATED WORKS

The closest works to APVAS are the aggregate path authentication [14] and APAT [15]. These works introduced aggregate signatures [12] in BGPsec (and S-BGP [16]) to aggregate individually generated signatures into a single short signature. However, they did not discuss the serious issue of memory consumption. Moreover, they did not provide improvements to aggregate signatures and a prototype implementation on a BGP software, which are our main technical contributions. Surprisingly, there is no commercial implementation of the original BGPsec itself [17] although BGPsec fully overcomes security concerns according to recent works [11, 18].

In the past years, BGP security research [19]–[21] aimed to serve a quick response with “decent” security by utilizing filtering instead of digital signatures. For example, the use of filtering can prevent 85% of hijacking [20], whereas paths can be repaired from a hijacking within a minute [21]. These results have shown how threats are mitigated in the real world. However, we mentioned that when the filtering-based approach is used, it is difficult to distinguish whether hijacking is done by a defense against DDoS or by an adversary from the standpoint of a third party.

III. BORDER GATEWAY PROTOCOL SECURITY EXTENSION (BGPsec)

In this section, we provide backgrounds on BGP hijacking, path validation, and the main problem of BGPsec.

A. Motivating Example: BGP Hijacking

As a motivating example of BGPsec, we explain route hijacking on BGP below. As described in Section II BGP is a protocol used for finding a route to a destination on the entire Internet in per AS unit. Each AS is assigned a unique AS number, and BGP uses these AS numbers to distinguish each AS and exchanges routing information via TCP. After a TCP connection is established, ASes exchange routing information with each other by sending and receiving an update message containing Network Layer Reachability Information (NLRI) and the AS_PATH.

\(^1\)BIRD: https://bird.network.cz/
these parameters. We describe the important parameters below:

**Target AS Number**: AS number of the destination of routing information.

**Signature Segment**: Digital signatures, where the number of the signatures is identical to the number of ASes that the routing information passed through excluding the route origin.

**Secure Path Segments**: AS numbers of ASes that the routing information passed through, where at least the AS number of the route origin is required.

**Algorithm Suite Identifier**: An identifier for specifying the signature algorithm used for signature generation.

**NLRI**: Values of network addresses and their subnet mask managed by the route origin.

### C. Problem Setting

Since an update message on BGPsec contains digital signatures, the size of the update message balloons and a big part of which comes from the digital signatures. National Institute of Standards and Technology (NIST) [22] has shown the estimation results for memory size of routers on BGPsec. According to NIST, a BGP update message has an average size of 78 bytes, while a BGPsec update message is 388 bytes to 1188 bytes in size depending on the signature algorithms. We recall the result with ECDSA-256 in Table I. In this table, the columns of Memory Size show total values with respect to routing tables registering destinations and those route attributes. Route information on BGPsec with respect to the world-wide level, i.e., full routes, requires a router to own more than 10 gigabytes of memory. Discussions and deployment of BGPsec have begun in 2016, and the deployment is estimated to finish in 2025. However, the complete deployment is nowhere in sight due to the memory size problem.

### IV. BIMODAL AGGREGATE SIGNATURES

In this section, we discuss the bimodal aggregate signature scheme used as a new building block in AVPs. In our proposed scheme, when $n$ users generate $n$ individual signatures, these signatures can be aggregated in two ways, i.e., an interactive style of general aggregate signatures [12] and a signature-chain style of sequential aggregate signatures [23].

Compared with conventional aggregate signatures [12], [23], bimodal aggregate signatures can provide the security of BGPsec by virtue of signature chains as well as the efficiency of aggregating individual signatures even on individual paths. Specifically, the security of BGPsec depends on signature chains and only the sequential aggregate signatures provide such chains via signature aggregation. On the other hand, to improve efficiency, i.e., reduce memory consumption, signatures even on individual paths should be aggregated, and such capability is inspired only by signature aggregation of the general aggregate signatures. In other words, when either one of the conventional aggregate signatures is deployed, only one of either the security or the efficiency is guaranteed. In contrast, the use of bimodal aggregate signatures can solve the memory size problem without sacrificing the security. We show the algorithms of the bimodal aggregate signature scheme below.

The proposed scheme is based on pairings defined as follows. Let $\mathbb{G}$ and $\mathbb{G}_T$ be groups with a prime order $p$. Then, a bilinear map $e : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ is a map with the following conditions: for any $U, V \in \mathbb{G}$ and $a, b \in \mathbb{Z}_p^*$, $e(aU, bV) = e(U, V)^{ab}$ holds; for any generator $P \in \mathbb{G}$, $e(P, P) \neq 1_{\mathbb{G}_T}$ holds, where $1_{\mathbb{G}_T}$ is an identity element in $\mathbb{G}_T$; and, for any $U, V \in \mathbb{G}$, $e(U, V)$ can be computed efficiently. We assume that solving the discrete logarithm problems in $\mathbb{G}$ and $\mathbb{G}_T$ is computationally hard. We call the parameter $(p, \mathbb{G}, \mathbb{G}_T, e)$ achieving the conditions above as a *pairing parameter*.

Hereafter, each signer is represented by a unique index $i$ in the algorithms for convenience. We denote by $S$ a set of signers for any signature and by $S_i$ a set of signers who join a chain of signatures from 1 to $i$ for any $i$. We also denote by $\|_i$ a concatenation of any string and by $\|_j$ concatenations of strings for any signer $j \in S_i$. We show the construction in Algorithms [1][5] The fourth line of Algorithm [5] and the third line of Algorithm [5] are identical to a signature chain, i.e., $\sigma$ indicates a signature. More precisely, $\sigma$ indicates a signature, and $e(\sigma, P)$ in Algorithm [5] and $e(c_j, X_i)$ in Algorithm [5] are identical to computations which are the main core for verification of signatures. Intuitively, by inputting signatures and their verifications to a hash function, the same signature chains are constructed. Even after $\sigma$s themselves are aggregated and lost, the corresponding $e(c_j, X_i)$’s can be computed. Therefore, both a signature chain of sequential aggregate signatures and an interactive aggregation of general

| Year | Number of Paths | Memory Size [GB] | Number of Paths | Memory Size [GB] |
|------|----------------|-----------------|----------------|-----------------|
| 2020 | 6332177        | 0.13            | 6332177        | 2.79            |
| 2021 | 44333466       | 0.09            | 10130562       | 4.47            |
| 2022 | 25472235       | 0.05            | 14201374       | 6.62            |
| 2023 | 1149812         | 0.02            | 18111088       | 7.99            |
| 2024 | 555617          | 0.01            | 21794419       | 9.61            |
| 2025 | 0              | 0               | 25472541       | 11.23           |
aggregate signatures can be provided simultaneously. The security of the proposed scheme can be proven formally under the computational Diffie-Hellman assumption in the random oracle model. We omit the details due to page limitation.

V. DESIGN OF APVAS

In this section, we present AS path validation based on aggregate signatures (APVAS) as a new path validation protocol for BGPsec. As described in Section II, APVAS is based on bimodal aggregate signatures. We first describe how bimodal aggregate signatures are deployed for path validation as a protocol specification. Then, we describe the prototype implementation on BIRD Internet routing daemon (BIRD), which is a software for BGP.

A. Protocol Specification

The specification of route advertisements on APVAS is shown in Fig. 5. Each intermediate AS takes information from the received update message and then verifies the routing information with Algorithm 5. Then, for the received routing information and aggregate signatures, an AS generates a new aggregate signature with Algorithm 5 and sends it to the neighbor ASes. Meanwhile, when an AS receives an update message including routing information from a different ORIGIN, the AS generates an aggregate signature as described above and then aggregates those signatures with Algorithm 5.

Signature Segment Format defined in the BGPsec protocol contains Subject Key Identifier (SKI) with size of 20 bytes, Signature Length with size of 2 bytes, and Signature with a variable length. In contrast, to contain only a single signature in APVAS, SKI is defined as SKI Segment with size of 20 bytes. The new Signature_Block Format of APVAS is shown in Fig. 6.

The proposed scheme, i.e., Algorithms 15 and 6 is utilized as the signature in APVAS as described above. We note that a plaintext \( m \) corresponds to a received update message. More precisely, for data storing shown in Fig. 4, the remaining string except for Signature Segment Format is utilized as \( m \). Likewise, for verification of update messages, the intermediate values of computation, i.e., outputs of bilinear maps, are utilized instead of a hashed value utilized for the previous signers to generate signatures because the update messages do not include the hashed values. Consequently, the size of update messages and the data size to be stored are reduced.

B. Prototype Implementation

We implement a prototype of APVAS by extending the BGPsec-enabled BIRD \(^3\), which is an implementation of BGPsec on BIRD, with a pairing library TEPLA\(^2\).

BIRD is a daemon software that utilizes a computer as a BGP router, and new functions can be introduced by writing in the C language. By editing a configuration file, we can set a router configuration and a network topology. The BGPsec-enabled Bird Routing Daemon \(^3\) is an extension of BIRD released by Secure Routing\(^4\) and we implemented the prototype of APVAS by extending the BGPsec-enabled Bird Routing Daemon.

Source codes related to BGP are in directories under proto/bgp/, and the codes to be improved are as follows:

\(^2\)TEPLA: http://www.cipher.risk.tsukuba.ac.jp/tepla/index.html
\(^3\)Secure Routing: http://www.securerouting.net/

Algorithm 3 SeqAggSign

Require: public parameter \( para \), secret key \( sk_i \), public key \( pk_i \), plaintext \( m_i \in \{0, 1\}^* \), list \( L = \{(pk_j, m_j)\}_{j \in S} \) of public keys and plaintexts, signature \( \sigma \)

Ensure: Signature \( \sigma \), list \( L' = \{(pk_j, m_j)\}_{j \in S} \cup \{(pk_i, m_i)\} \) of public keys and plaintexts

1: if \( L = \emptyset \) then
2: \( \sigma = 0 \)
3: end if
4: \( c = H(e(\sigma, P)) \parallel pk_i \parallel m_i \parallel_{j \in S} (pk_j || m_j) \)
5: \( \sigma = \sigma + x \cdot H(c) \)

Algorithm 4 AggSign

Require: public parameter \( para \), list \( L_1 = \{(pk_j, m_j)\}_{j \in S} \) of public keys and plaintexts, list \( L_2 = \{(pk_j, m_j)\}_{j \in S'} \) of public keys and plaintexts, signature \( \sigma_1 \), signature \( \sigma_2 \)

Ensure: signature \( \sigma \), list \( L' = L_1 \cup L_2 \)

1: \( \sigma = \sigma_1 + \sigma_2 \)

Algorithm 5 Verify

Require: public parameter \( para \), list \( L = \{(pk_j, m_j)\}_{j \in S} \) of public keys and plaintexts, signature \( \sigma \)

Ensure: True or False

1: For any \( i \in S \), parse \( pk_i \) as \( X_i \)
2: if all \( (pk_i, m_i) \in S \) are distinct then
3: \( \forall i, c_i = H \left( \prod_{j \in S} e(c_j, X_i) \right) \parallel_{j \in S} (pk_j || m_j) \)
4: if \( e(\sigma, P) = \prod_{i \in S} e(H(c_i), X_i) \) then
5: \( \text{return True} \)
6: end if
7: end if
8: \( \text{return False} \)
follows. First, we improve encoding and decoding of update messages by modifying the `encode_bgpsec_attr()` function and the `decode_bgpsec_attr()` function in `attrs.c`, respectively. We also improve signature generation and verification by replacing the `bgpsec_sign_data_with_key()` function and the `bgpsec_verify_signature_with_key()` function in `validate.c`, respectively, with an implementation of the bimodal aggregate signatures with TEPLA. The parameters utilized in pairing computation are shown in Table II.

### VI. EXPERIMENTS

We created a prototype implementation of APVAS and conducted experiments on a virtual network with a simple topology to evaluate the memory consumption of APVAS and compare it with the results of the conventional method. The main purpose of our experiments is to take a first step in understanding the performance, i.e., in terms of memory consumption, of APVAS on actual devices.

#### A. Experimental Environment

While BIRD can deal with many kinds of network topologies, a linear network is the simplest network topology for understanding the relationship between the number of paths and the average AS_PATH length. In such a topology, AS routers are connected with each other in a linear manner. Moreover, the number of paths advertised to the network is the total number of paths statically advertised by each AS, and the average AS_PATH length is an average of distances between ASes which advertise the paths. In the experiment described below, we focus on a linear network to evaluate APVAS.

Six virtual routers are configured under the machine environment shown in Table III and private AS numbers from 65001 to 65006 are assigned to these routers, respectively. Each router is assigned a static IP from 192.168.0.201 to 206 in accordance with the lowest digit of its own AS number, and the routers connect with each other to configure the network. For example, when AS65001 advertises routing information, the other ASes receive the same routing information. In doing so, the average AS_PATH length is identical to a difference between AS numbers, making the evaluation of data easy. Since the upper bound for route advertisement whereby BIRD works stably is 250 according to our pre-experiments, we adopt the number of paths advertised by AS65001 from 50, 100, 150, 200, and 250, respectively. For instance, in a case where AS65001 advertises 200 paths to AS65004, the latter AS receives the 200 paths whose AS_PATH length is 3. In the setting described above, the memory consumption for routers owning 200 paths with length 3 can be estimated.

### TABLE II

**VERSION OF LIBRARY AND UTILIZED PARAMETERS**

| TEPLA ver. | 2.0 |
|------------|-----|
| Pairing    | ECBN254a |
| Finite Field | bn254_fpa |
| P (Pre-generated) | 1462ca218754f628c4... |

### TABLE III

**ENVIRONMENT**

| OS               | Ubuntu 16.04 LTS |
|------------------|------------------|
| CPU              | Intel Core i7-6500U |
| Memory           | 1 GB |
| VMware ver.      | Workstation Pro 14.1.2 |
| BIRD ver.        | 1.6.0 |
| BIRD BGPsec ver. | 0.9 |

### TABLE IV

**MEMORY SIZE OF APVAS (WITH 200 PATHS)**

| AS Number    | 65002 | 65003 | 65004 | 65005 | 65006 |
|--------------|-------|-------|-------|-------|-------|
| Routing Table| 46    | 46    | 46    | 46    | 46    |
| Route Attribute | 116  | 122   | 128   | 134   | 140   |

We evaluate the memory consumption of AS65002 to AS65006 based on the environment described above. Note that the process of obtaining a pair of secret and public keys is outside the scope of the experiment. We suppose that the pair of keys is generated and installed on each router in advance. Likewise, routing information for advertisement is randomly generated in advance.

#### B. Results

The memory consumption when each AS receives 200 paths is shown in Table IV. The table shows only the memory size related to routing tables and route attributes, although BIRD includes the routing tables, route attributes, Route Origin Authorization (ROA) table, and the protocol information. APVAS is successful in reducing the memory size in comparison with the conventional BGPsec because the sizes of other information in the current specification [8], e.g., ROA tables and the protocol itself, are stable in our experiment. The results of the memory consumption under the same setting for BGP routers and the conventional BGPsec routers are shown in Table V and Table VI respectively, and the entire data is visualized in the continuous lines of Fig. 7.

The results show that the memory size of APVAS is smaller than that of the conventional BGPsec. The memory size of APVAS becomes larger at the average AS_PATH length 1 because of the data size of the bimodal aggregate signatures. More precisely, while the conventional BGPsec utilizes ECDSA with bit length of 384 bits per signature, the bimodal aggregate signatures have bit length of 512 bits.

#### C. Consideration

According to the empirical study of Wang et al. [25], the average AS_PATH length on the Internet is about 3.9 and the longest path is about 20. When the average AS_PATH length is 4, the size of route attributes by APVAS became 80% less than the conventional BGPsec. The bulk of memory consumption is related to the size of route attributes [22], and thus the results above confirm that APVAS can reduce memory consumption by 80%. Furthermore, the memory consumption until length 20 can be estimated by the least squares method.
TABLE V
MEMORY SIZE OF BGP ROUTERS (WITH 200 PATHS)

| AS Number | 65002 | 65003 | 65004 | 65005 | 65006 |
|-----------|-------|-------|-------|-------|-------|
| Routing Table | 46    | 46    | 46    | 46    | 46    |
| Route Attribute | 10    | 10    | 10    | 10    | 10    |

TABLE VI
MEMORY SIZE OF BGPSec ROUTERS (WITH 200 PATHS)

| AS Number | 65002 | 65003 | 65004 | 65005 | 65006 |
|-----------|-------|-------|-------|-------|-------|
| Routing Table | 46    | 46    | 46    | 46    | 46    |
| Route Attribute | 104   | 124   | 144   | 164   | 188   |

VI. CONCLUSION

In this paper, we proposed APVAS, a path validation method that deploys novel bimodal aggregate signatures to reduce memory consumption on BGPSec. We implemented a prototype of APVAS via BIRD and measured the memory consumption with actual routers. Our experimental results confirm that APVAS can reduce memory consumption by 80% in comparison with conventional BGPSec. We are preparing for the release of our implementation of APVAS to encourage development of BGPSec and future works. We hope that APVAS will serve as a base for future studies on BGPSec.

We plan to experiment further with full routes as future work. Although the experiments in this paper were conducted on a linear network as the simplest topology as the first step of a long way to practical realization, the performance in an environment with full routes should be clarified before deployment in the world-wide level. Furthermore, we discovered a new problem where the throughput of routers is downgraded by the computational cost of bimodal aggregate signatures, which is heavier than that of ECDSA. Thus, further studies on reducing not only the memory consumption but also the computational cost, which takes misconfiguration such that a large amount of routing information is advertised into account, will need to be undertaken.

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