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A. Azimov  
Yandex  
E. Bogomazov  
Qrator Labs  
R. Bush  
Internet Initiative Japan & Arrcus  
K. Patel  
Arrcus, Inc.  
J. Snijders  
NTT  
March 9, 2020

Verification of AS\_PATH Using the Resource Certificate Public Key  
Infrastructure and Autonomous System Provider Authorization  
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Abstract

This document defines the semantics of an Autonomous System Provider Authorization object in the Resource Public Key Infrastructure to verify the AS\_PATH attribute of routes advertised in the Border Gateway Protocol.

Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

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## 1. Introduction

The Border Gateway Protocol (BGP) was designed without mechanisms to validate BGP attributes. Two consequences are BGP Hijacks and BGP Route Leaks [RFC7908]. BGP extensions are able to partially solve these problems. For example, ROA-based Origin Validation [RFC6483] can be used to detect and filter accidental mis-originations, and [I-D.ietf-grow-route-leak-detection-mitigation] can be used to detect accidental route leaks. While these upgrades to BGP are quite useful, they still rely on transitive BGP attributes, i.e. AS\_PATH, that can be manipulated by attackers.

BGPsec [RFC8205] was designed to solve the problem of AS\_PATH validation. Unfortunately, strict cryptographic validation brought

expensive computational overhead for BGP routers. BGPsec also proved vulnerable to downgrade attacks that nullify the benefits of AS\_PATH signing. As a result, to abuse the AS\_PATH or any other signed transit attribute, an attacker merely needs to downgrade to 'old' BGP-4.

An alternative approach was introduced with soBGP [I-D.white-sobgp-architecture]. Instead of strong cryptographic AS\_PATH validation, it created an AS\_PATH security function based on a shared database of ASN adjacencies. While such an approach has reasonable computational cost, the two side adjacencies don't provide a way to automate anomaly detection without high adoption rate - an attacker can easily create a one-way adjacency. SO-BGP transported data about adjacencies in new additional BGP messages, which was recursively complex thus significantly increasing adoption complexity and risk. In addition, the general goal to verify all AS\_PATHs was not achievable given the indirect adjacencies at internet exchange points.

Instead of checking AS\_PATH correctness, this document focuses on solving real-world operational problems - automatic detection of malicious hijacks and route leaks. To achieve this a new AS\_PATH verification procedure is defined which is able to automatically detect invalid (malformed) AS\_PATHs in announcements that are received from customers and peers. This procedure uses a shared signed database of customer-to-provider relationships using a new RPKI object - Autonomous System Provider Authorization (ASPA). This technique provides benefits for participants even during early and incremental adoption.

## 2. Anomaly Propagation

Both route leaks and hijacks have similar effects on ISP operations - they redirect traffic, resulting in increased latency, packet loss, or possible MiTM attacks. But the level of risk depends significantly on the propagation of the anomalies. For example, a hijack that is propagated only to customers may concentrate traffic in a particular ISP's customer cone; while if the anomaly is propagated through peers, upstreams, or reaches Tier-1 networks, thus distributing globally, traffic may be redirected at the level of entire countries and/or global providers.

The ability to constrain propagation of BGP anomalies to upstreams and peers, without requiring support from the source of the anomaly (which is critical if source has malicious intent), should significantly improve the security of inter-domain routing and solve the majority of problems.

### 3. Autonomous System Provider Authorization

As described in [RFC6480], the RPKI is based on a hierarchy of resource certificates that are aligned to the Internet Number Resource allocation structure. Resource certificates are X.509 certificates that conform to the PKIX profile [RFC5280], and to the extensions for IP addresses and AS identifiers [RFC3779]. A resource certificate is a binding by an issuer of IP address blocks and Autonomous System (AS) numbers to the subject of a certificate, identified by the unique association of the subject's private key with the public key contained in the resource certificate. The RPKI is structured so that each current resource certificate matches a current resource allocation or assignment.

ASPA is digitally signed object that bind, for a selected AFI, a Set of Provider AS numbers to a Customer AS number (in terms of BGP announcements not business), and are signed by the holder of the Customer AS. An ASPA attests that a Customer AS holder (CAS) has authorized Set of Provider ASes (SPAS) to propagate the Customer's IPv4/IPv6 announcements onward, e.g. to the Provider's upstream providers or peers. The ASPA record profile is described in [I-D.ietf-sidrops-aspa-profile]. For a selected Customer AS MAY exist only single ASPA object.

### 4. Customer-Provider Verification Procedure

This section describes an abstract procedure that checks that a pair of ASNs (AS1, AS2) is included in the set of signed ASPAs. The semantics of its use is defined in next section. The procedure takes (AS1, AS2, ROUTE\_AFI) as input parameters and returns one of three results: "valid", "invalid" and "unknown".

A relying party (RP) must have access to a local cache of the complete set of cryptographically valid ASPAs when performing customer-provider verification procedure.

1. Retrieve cryptographically valid ASPA in a selected AFI with a customer value of AS1. If there is no valid ASPA record for AS1 the procedure exits with an outcome of "unknown."
2. If AS2 is included in the SPAS, then the procedure exits with an outcome of "valid."
3. Otherwise, the procedure exits with an outcome of "invalid."

Since an AS1 may have different set providers in different AFI, it should also have different PCAS in corresponding ASPAs. In this

case, the output of this procedure with input (AS1, AS2, ROUTE\_AFI) may have different output for different ROUTE\_AFI values.

## 5. AS\_PATH Verification

The AS\_PATH attribute identifies the autonomous systems through which an UPDATE message has passed. AS\_PATH may contain two types of components: ordered AS\_SEQs and unordered AS\_SETs, as defined in [RFC4271].

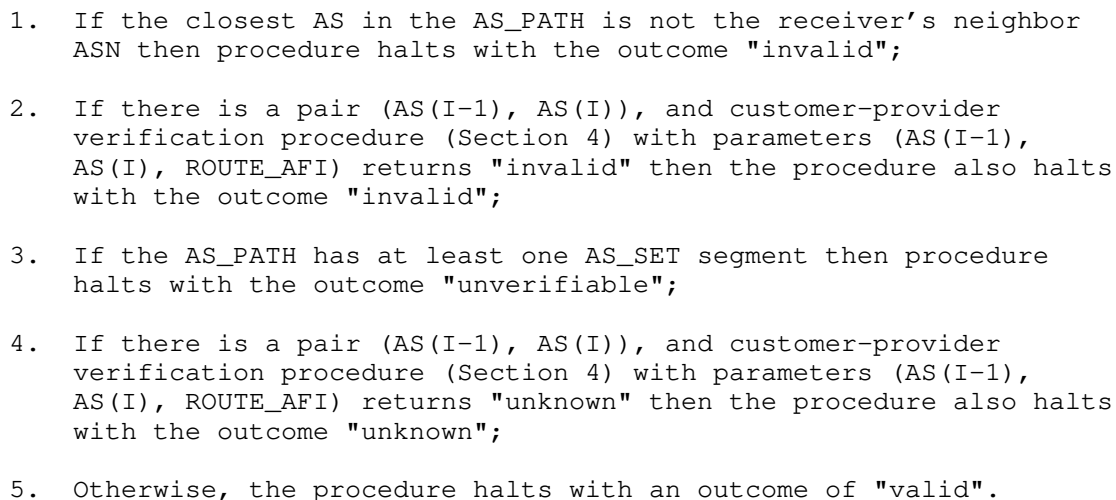
The value of each concatenated value of AS\_SEQ components can be described as set of pairs {(AS(I), prepend(I)), (AS(I-1), prepend(I-1))...}, where AS(0) stands for originating AS. In this case, the sequence {AS(I), AS(I-1),...} represents different ASNs, that packet should pass towards the destination.

The bellow procedure is applicable only for 32-bit AS number compatible BGP speakers.

### 5.1. Upstream Paths

When a route is received from a customer, a literal peer, or by a RS at an IX, each pair (AS(I-1), AS(I)) MUST belong to customer-provider or sibling relationship. If there are other types of relationships, it means that the route was leaked or the AS\_PATH attribute was malformed. The goal of the procedure described bellow is to check the correctness of this statement.

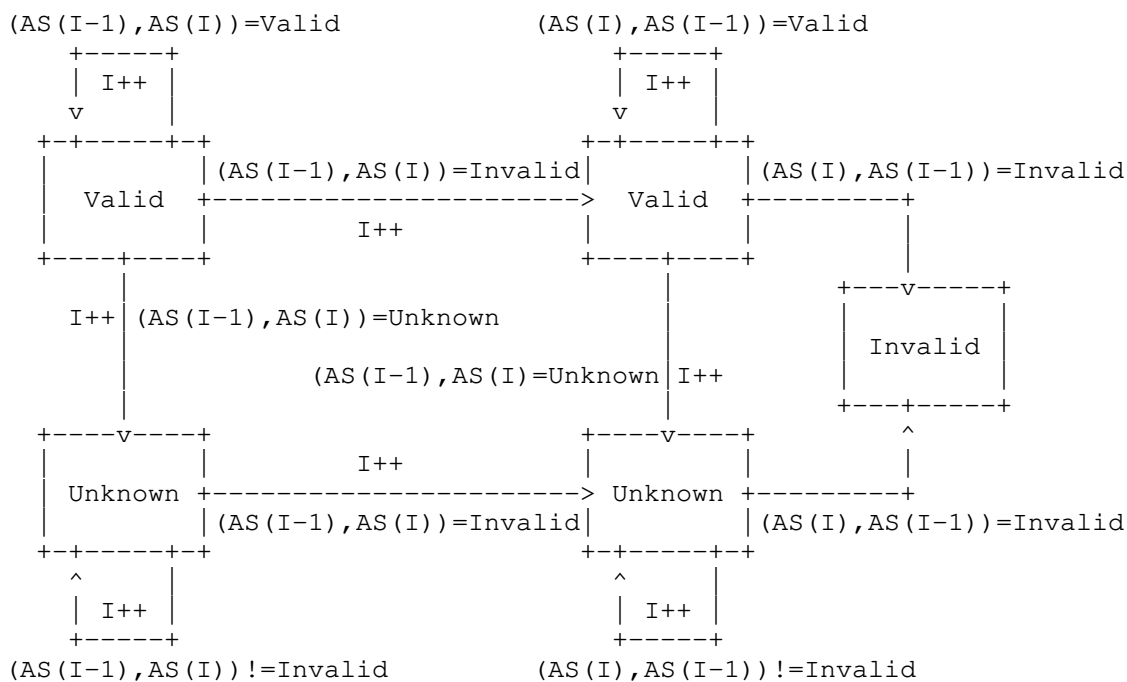
The following diagram and procedure describes the procedure that MUST be applied on routes with ROUTE\_AFI received from a customer, peer or RS-client:



followed by Upstream path it means that the route was leaked or the AS\_PATH attribute was malformed. The first pair (AS(I-1), AS(I)) that has an "invalid" outcome of the customer-provider verification procedure indicates the end of the Upstream path. All subsequent reverse pairs (AS(I), AS(I-1)) MUST belong to a customer-provider or sibling relationship, thus can be also verified using ASPA objects.

Additional caution should be exercised when processing prefixes that are received from transparent IXes, as they don't add their ASN in the ASPATH.

The following diagram and procedure describe the procedure that MUST be applied on routes with ROUTE\_AFI received from a provider or a RS:



1. If a route is received from a provider and the closest AS in the AS\_PATH is not the receiver's neighbor ASN, then the procedure halts with the outcome "invalid";
2. If there are two pairs (AS(I-1), AS(I)), (AS(J-1), AS(J)) with J > I, and the customer-provider verification procedure (Section 4) returns "invalid" for both (AS(I-1), AS(I), ROUTE\_AFI) and (AS(J), AS(J-1), ROUTE\_AFI), then the procedure also halts with the outcome "invalid";

3. If the AS\_PATH has at least one AS\_SET segment then procedure halts with the outcome "unverifiable";
4. If there are two pairs (AS(I-1), AS(I)), (AS(J-1), AS(J)) with  $J > I$ , and the customer-provider verification procedure (Section 4) returns "invalid" for (AS(I-1), AS(I), ROUTE\_AFI) and "unknown" for (AS(J), AS(J-1), ROUTE\_AFI), then the procedure also halts with the outcome "unknown";
5. If the customer-provider verification procedure (Section 4) doesn't return "invalid" for any (AS(I-1), AS(I)), but at least for one (AS(I-1), AS(I)) returns "unknown", then the procedure also halts with the outcome "unknown";
6. Otherwise, the procedure halts with an outcome of "valid".

### 5.3. Mitigation

If the output of the AS\_PATH verification procedure is "invalid" the route MUST be rejected.

If the output of the AS\_PATH verification procedure is 'unverifiable' it means that AS\_PATH can't be fully checked. Such routes should be treated with caution and SHOULD be processed the same way as "invalid" routes. This policy goes with full correspondence to [I-D.kumari-deprecate-as-set-confed-set].

The above AS\_PATH verification procedure is able to check routes received from customers and peers. The ASPA mechanism combined with BGP Roles [I-D.ietf-idr-bgp-open-policy] and ROA-based Origin Validation [RFC6483] provide a fully automated solution to detect and filter hijacks and route leaks, including malicious ones.

### 6. Disavowal of Provider Authorizaion

An ASPA is a positive attestation that an AS holder has authorized its providers to redistribute received routes to the provider's providers and peers. This does not preclude the provider ASes from redistribution to its other customers. By creating an ASPA with providers set of {0}, the customer indicates that no provider should further announce its routes. Specifically, AS 0 is reserved to identify provider-free networks, Internet exchange meshes, etc.

An ASPA with a providers set of {0} is a statement by the customer AS that its routes should not be received by any relying party AS from any of its customers or peers.



By convention, an ASPA with a provider set of {0} should be the only ASPA issued by a given AS holder; although this is not a strict requirement. A provider AS 0 may coexist with other provider ASes in the same ASPA (or other ASPA records); though in such cases, the presence or absence of the provider AS 0 in ASPA does not alter the AS\_PATH verification procedure.

## 7. Siblings (Complex Relations)

There are peering relationships which can not be described as strictly simple peer-peer or customer-provider; e.g. when both parties are intentionally sending prefixes received from each other to their peers and/or upstreams.

In this case, two corresponding ASPA records (AS1, {AS2, ...}), (AS2, {AS1, ...}) must be created by AS1 and AS2 respectively.

## 8. Security Considerations

The proposed mechanism is compatible only with BGP implementations that can process 32-bit ASNs in the ASPATH. This limitation should not have a real effect on operations - such legacy BGP routers are rare and it's highly unlikely that they support integration with the RPKI.

ASPA issuers should be aware of the verification implication in issuing an ASPA - an ASPA implicitly invalidates all routes passed to upstream providers other than the provider ASs listed in the ASPA record. It is the Customer AS's duty to maintain a correct set of providers in ASPA record(s).

While it's not restricted, but it's highly recommended maintaining for selected Customer AS a single ASPA object that covers all its providers. Such policy should prevent race conditions during ASPA updates that might affect prefix propagation.

While the ASPA is able to detect both mistakes and malicious activity for routes received from customers, RS-clients, or peers, it provides only detection of mistakes for routes that are received from upstream providers and RS(s).

Since an upstream provider becomes a trusted point, it will be able to send hijacked prefixes of its customers or send hijacked prefixes with malformed AS\_PATHs back. While it may happen in theory, it's doesn't seem to be a real scenario: normally customer and provider have a signed agreement and such policy violation should have legal consequences or customer can just drop relation with such a provider and remove the corresponding ASPA record.

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#### Authors' Addresses

Alexander Azimov  
Yandex

Email: [a.e.azimov@gmail.com](mailto:a.e.azimov@gmail.com)

Eugene Bogomazov  
Qrator Labs

Email: eb@qrator.net

Randy Bush  
Internet Initiative Japan & Arrcus

Email: randy@psg.com

Keyur Patel  
Arrcus, Inc.

Email: keyur@arrcus.com

Job Snijders  
NTT Communications  
Theodorus Majofskistraat 100  
Amsterdam 1065 SZ  
The Netherlands

Email: job@ntt.net