BGP Origin Validation

ISP Workshops

Last updated 19th January 2022

Acknowledgements

- This material was built from contributions by Randy Bush, Mark Tinka, Aftab Siddiqui, Tashi Phuntsho and others

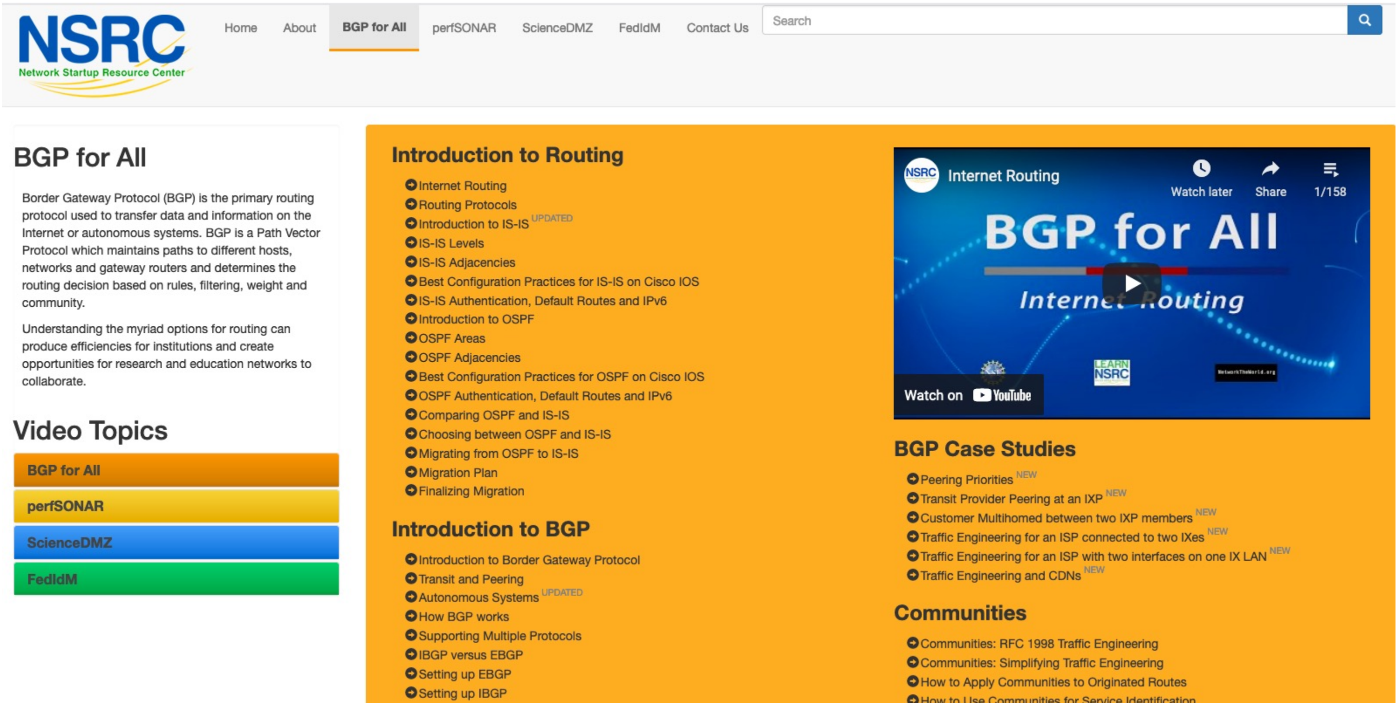
- Use of these materials is encouraged as long as the source is fully acknowledged and this notice remains in place

- Bug fixes and improvements are welcomed
  - Please email *workshop (at) bgp4all.com*

Philip Smith

BGP Videos

- NSRC has produced a library of BGP presentations (including this one), recorded on video, for the whole community to use
  - https://learn.nsrc.org/bgp



Validating BGP Route Announcements

- How do we know that an AS is permitted to originate the prefix it is originating?
- Implicit trust?
- Because the Internet Routing Registry says so?
  - The Internet Routing Registry (IRR) only documents routing policy
  - And has a large amount of outdated/incorrect information
- Is there something else?
  - Yes: Route Origin Authorisation

BGP – Why Origin Validation?

- Prevent YouTube accident & Far Worse
  - Almost every day there is an incident of prefix hijack somewhere on the Internet
- Prevents most accidental announcements
  - “Fat finger”, missing BGP policy configuration, etc
- Does not prevent malicious path attacks
  - Example: alteration of AS-PATH attribute along the announcement chain
  - That requires ‘Path Validation’, using BGPsec

RPKI

- RPKI – Resource Public Key Infrastructure
  - The Certificate Infrastructure for origin and path validation

- We need to be able to authoritatively prove who owns an IP prefix and which AS(s) may announce it
  - Prefix ownership follows the allocation hierarchy
  - IANA → RIRs → ISPs → etc

What is RPKI?

- Resource Public Key Infrastructure (RPKI)
  - A security framework for verifying the association between resource holder and their Internet resources
  - Created to address the issues discussed in RFC 4593 "Generic Threats to Routing Protocols" (Oct 2006)
- Helps to secure Internet routing by validating routes
  - Proof that prefix announcements are coming from the legitimate holder of the resource
  - RFC 6480 – An Infrastructure to Support Secure Internet Routing (Feb 2012)
  - RFC 7115 – Origin Validation Operation Based on the Resource Public Key Infrastructure (RPKI)

Benefits of RPKI for Routing

- Prevents route hijacking
  - A prefix originated by an AS without authorisation
  - Reason: malicious intent
- Prevents mis-origination
  - A prefix that is mistakenly originated by an AS which does not own it
  - Also, route leakage
  - Reason: configuration mistake / fat finger

BGP Security (BGPsec)

- Extension to BGP that provides improved security for BGP routing
  - Published as RFC8205
  - Not yet deployed
- Implemented via a new optional non-transitive BGP attribute (BGPsec_PATH) that contains a digital signature
- BGPsec supplements BGP origin validation
  - Allows routers to generate, propagate, and validate BGP update messages with the BGPsec_PATH attribute set

BGPsec Components

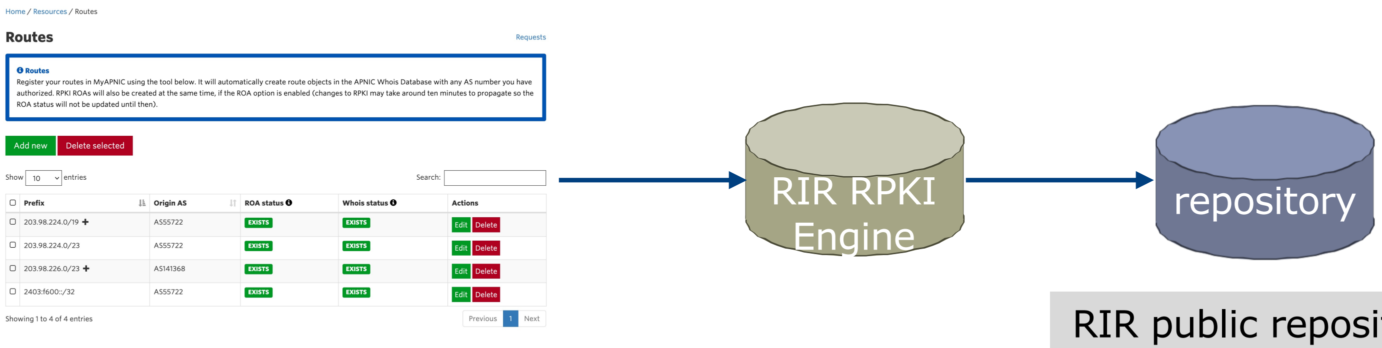
- Origin Validation
  - Using the RPKI to detect and prevent mis-originations of someone else's prefixes (RFC6483)
  - Implementation started in 2012
- AS-Path Validation
  - BGPsec has not yet begun deployment (cryptographic computation load)
  - soBGP was one early option
    - https://datatracker.ietf.org/doc/draft-white-sobgp-architecture/ (expired)
    - Not standardised or implemented
  - ASPA (Autonomous System Provider Authorisation) is the most promising interim step prior to full BGPsec deployment
    - https://datatracker.ietf.org/doc/draft-ietf-sidrops-aspa-verification/

RPKI Nomenclature

- Issuing Party
  - The entity operating as certificate authority (CA)
- Trust Anchor
  - The authority from which trust is assumed, rather than derived from intermediates – the root of the tree
- Relying Party
  - The operator system gathering data from the certificate authority to be used for validation
- Route Origin Authorisation
  - An digital object linking an AS number with the IP address space it is authorised to originate

Issuing Party

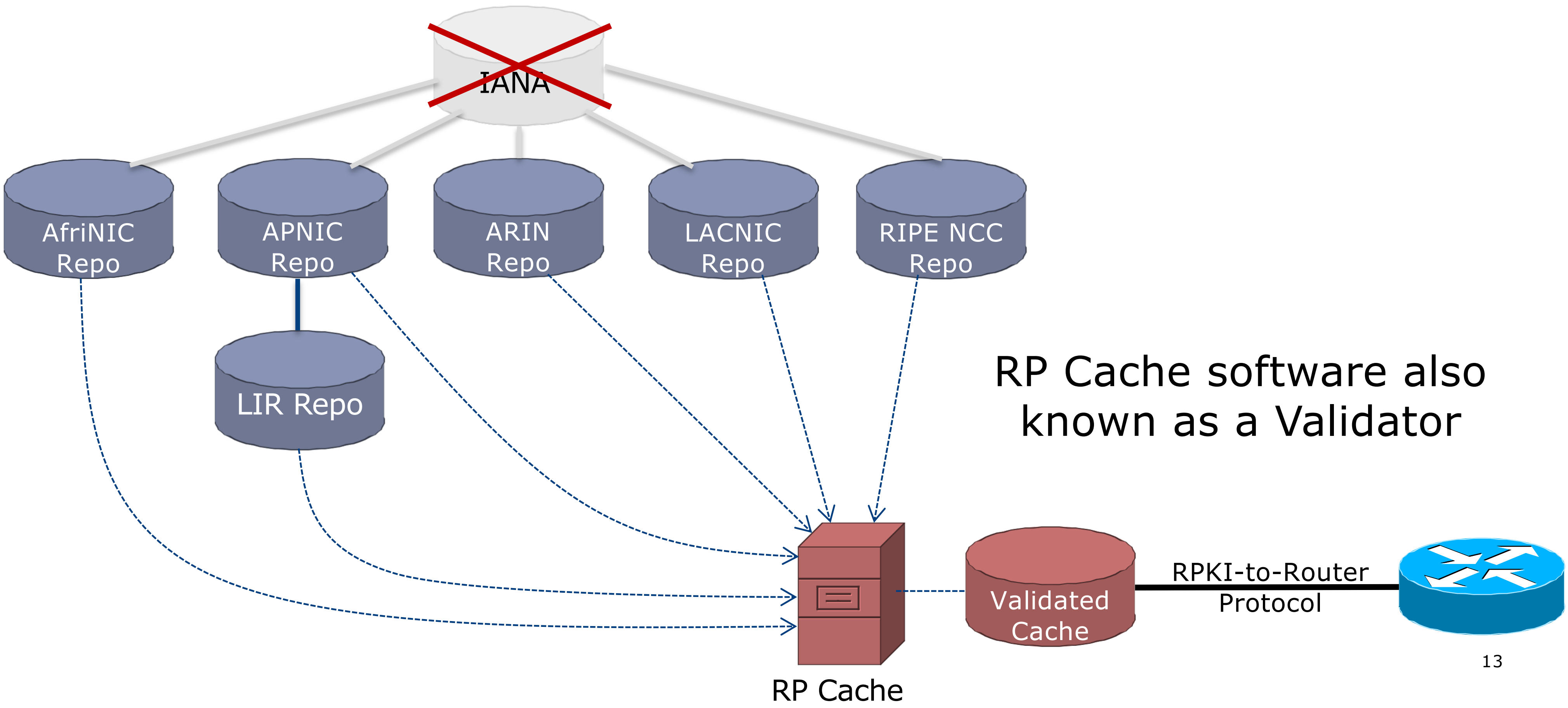
- Internet Registries (RIR, NIR, Large LIRs)
- Acts as a Certificate Authority and issues certificates for customers
- Provides a web interface to issue ROAs for customer prefixes
- Publishes the ROA records



RIR public repository

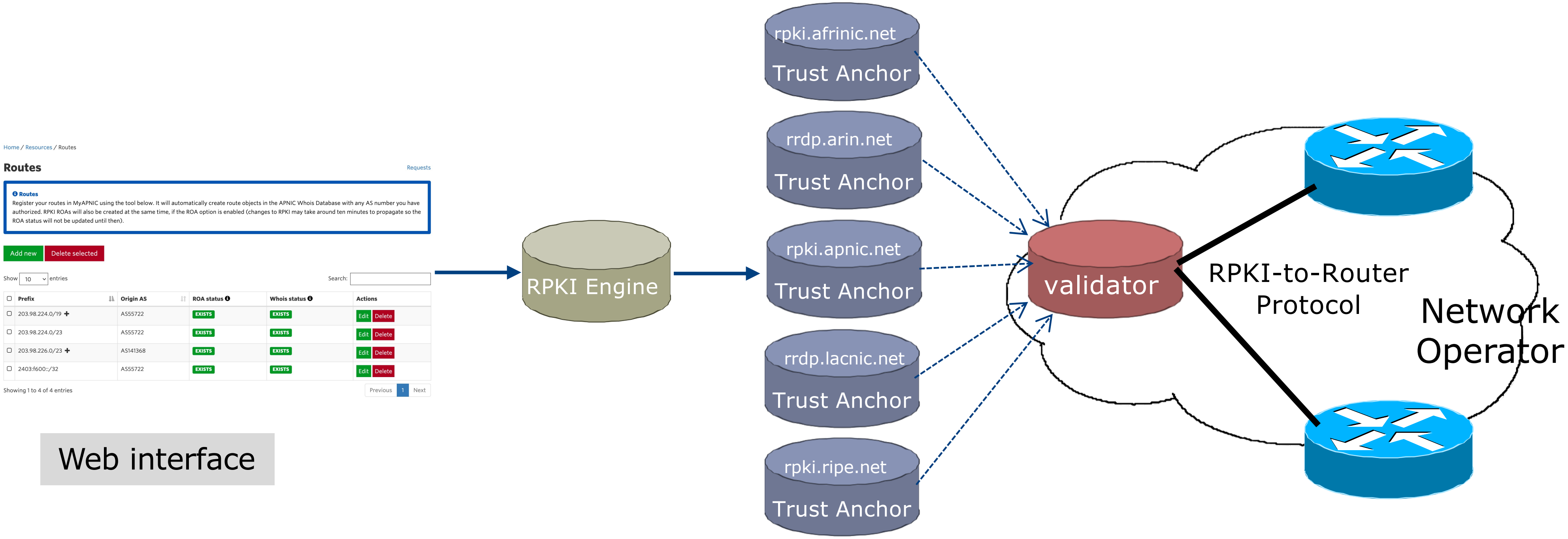
RIR web interface

Relying Party (RP)



RP Cache software also known as a Validator

RPKI Components



Web interface

Each of the RIRs publishes their "Trust Anchor Locator" (TAL) – the file that contains both the URL of the RPKI repository and the public key

RPKI Service Models

- Hosted Model:
  - The RIR runs the CA on behalf of its members
    - Manage keys, repository, etc
    - Generate certificates for resource certifications
- Delegated Model:
  - Member becomes the CA, delegated from the parent CA (the RIR)
    - Operates the full RPKI system
    - Several entities now operating delegated CAs
  - CA Software
    - NLnetLabs Krill: https://www.nlnetlabs.nl/projects/rpki/krill/

Route Origin Authorisation (ROA)

- A digital object that contains a list of address prefixes and one AS number
- It is an authority created by a prefix holder to authorise an AS Number to originate one or more specific route advertisements
- Publish a ROA using your RIR member portal
  - Consult your RIR for how to use their member portal to publish your ROAs

Route Origin Authorisation

- A typical ROA would look like this:

Prefix	10.10.0.0/16
Max-Length	/18
Origin-AS	AS65534

- There can be more than one ROA per address block
  - Allows the operator to originate prefixes from more than one AS
  - Caters for changes in routing policy or prefix origin

Creating ROAs

- Only create ROAs for the aggregate and the exact subnets expected in the routing table
- Examples:

Prefix	Max Length	Origin AS	Comments
10.10.0.0/16	/24	65534	ROA covers /16 through to /24 – any announced subnets to /24 will be Valid if from AS65534
10.10.0.0/16	/16	65534	ROA covers only /16 – any announced subnets will be Invalid
10.10.4.0/22	/24	65534	ROA covers this /22 through to /24
10.10.32.0/22	/24	64512	Valid ROA covers /22 through to /24 announcements from AS64512

Creating ROAs – Important Notes

- Always create ROAs for the aggregate and the individual subnets being routed in BGP
- Example:
  - If creating a ROA for 10.10.0.0/16 **and** “max prefix” length is set to /16
    - There will only be a valid ROA for 10.10.0.0/16
    - If a subnet of 10.10.0.0/16 is originated, it will be state Invalid

Creating ROAs – Important Notes

- Avoid creating ROAs for subnets of an aggregate unless they are actually being actively routed
  - If ROA exists, but subnet is not routed, it leaves an opportunity for someone else to mis-originate the subnet using the valid origin AS, resulting in a hijack

- https://datatracker.ietf.org/doc/draft-ietf-sidrops-rpkimaxlen/ has a good description of the care needed when creating ROAs
  - Recommendations:
    - Avoid using maxLength attribute unless in special cases
    - Use minimal ROAs wherever possible – only for prefixes that are actually being announced
  - Also a discussion about ROAs for facilitating DDoS Services
  - There is even a strong suggestion that "maxLength" should be deprecated

Creating ROAs – Important Notes

- Some current examples of problematic ROAs:

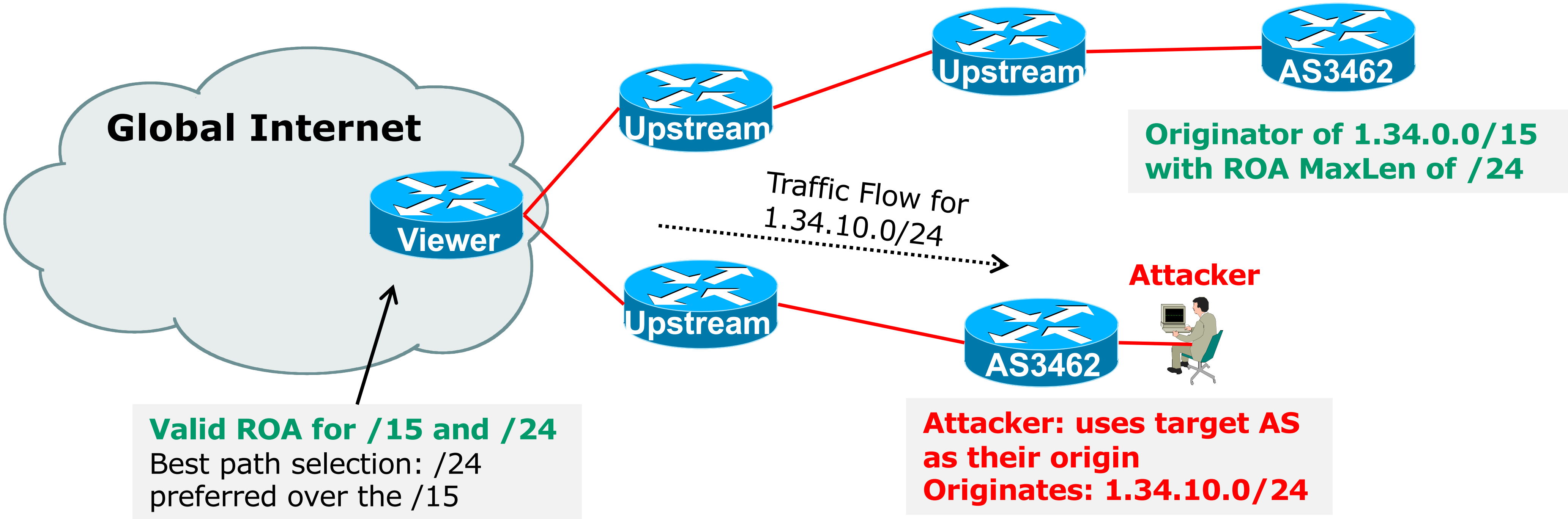
328037	2c0f:f0c8::/32	128

  - This means that any and every subnet of 2C0F:F0C8::/32 originated by AS328037 is valid
    - An attacker can use AS328037 as their origin AS to originate 2C0F:F0C8:A0:/48 to deny service to that address block
    - Known as a validated hijack!

3462	1.34.0.0/15	24

  - This means that any subnet of 1.34.0.0/15 down to a /24 as originated by AS3462 is valid
    - An attacker can use AS3462 as their origin AS to originate 1.34.10.0/24 to deny service to that address block

Creating ROAs: "Validated Hijack"



- If the 1.34.10.0/24 prefix had had no ROA, route origin validation would have dropped the invalid announcement at the upstream AS

Creating ROAs: pre-RIR Address Space

- Some entities were assigned address space by InterNIC
  - This is prior to the existence of the RIRs
- How to sign ROAs for these resources?
- Some RIRs will support the signing of legacy address space ROAs
  - If there is documentation proving the holding
  - If there is some service agreement for resources allocated by the RIR
  - Or by some other arrangement
  - Example, APNIC:
    - https://www.apnic.net/wp-content/uploads/2018/02/APNIC-AR-2017.pdf
  - Example, RIPE NCC:
    - https://www.ripe.net/manage-ips-and-asns/resource-management/certification/resource-certification-rpki-for-provider-independent-end-users

Route Origin Validation

- Router must support RPKI
- Checks an RP cache / validator
  - Uses RtR protocol, described in RFC8210
- Validation returns 3 states:

State	Description
Valid	When authorisation is found for prefix X coming from ASN Y
Invalid	When authorisation is found for prefix X but **not** from ASN Y, or **not** allowable subnet size
Not Found	When no authorisation data is found for prefix X

Route Origin Validation – AS0

- RFC6483 also describes "Disavowal of Routing Origination"
  - AS 0 has been reserved for network operators and other entities to identify non-routed networks
  - Which means:
    - "A ROA with a subject of AS0 (AS0 ROA) is an attestation by the holder of a prefix that the prefix described in the ROA, and any more specific prefix, should not be used in a routing context"
- Any prefixes with ROA indicating AS0 as the origin AS need to be dropped
  - If these prefixes appear with any other origin, their ROAs will be invalid, achieving this goal

Route Origin Validation – AS0

- Possible use cases of AS0:
  - Internal use of a prefix that should not appear in the global BGP table
  - Internet Exchange Point LAN must never appear in the global BGP table
  - Private Address space (IPv4) and non-Global Unicast space (IPv6)
  - Unassigned address space
    - This is under discussion within the various RIR policy fora
  - IPv4 and IPv6 address resources which should not appear in the global BGP table
    - For example, the special use address space described in RFC6890

Route Origin Validation – AS0

- APNIC & LACNIC have now published their AS0 TALs
  - Operated separately from the regular TAL
    - https://www.apnic.net/community/security/resource-certification/trust-anchor-locator/
    - https://www.lacnic.net/4984/2/lacnic/rpki-rpki-trust-anchor
  - Simply add to the TAL folder in the validator cache
- Some examples of AS0 being used today:

```
RPKI/RTR prefix table
Prefix                                   Prefix Length  Origin-AS
2.57.180.0                                  22 -  24            0
5.57.80.0                                   22 -  22            0
23.4.85.0                                   24 -  24            0
23.173.176.0                                24 -  24            0
23.211.114.0                                23 -  24            0
45.12.44.0                                  22 -  22            0
58.181.75.0                                 24 -  24            0
109.122.244.0                               22 -  22            0
```

Route Origin Validation – Implementations

- Cisco IOS – available from release 15.2
- Cisco IOS/XR – available from release 4.3.2
- Juniper JunOS – available from release 12.2
- Nokia – available from release R12.0R4
- Huawei – available from release V800R009C10
- FRR – available from release 4.0
- BIRD – available from release 1.6
- OpenBGPD – available from OpenBSD release 6.4
- GoBGP – available since 2018
- VyOS – available from release 1.2.0-RC11
- Mikrotik ROS – available from release v7
- Arista EOS – available from release 4.24.0F

RPKI Validator Caches (1)

- NLnet Labs Routinator 3000
  - https://www.nlnetlabs.nl/projects/rpki/routinator/
  - https://github.com/NLnetLabs/routinator
  - Packages available for Debian/Ubuntu, RHEL/CentOS & FreeBSD
  - (Can also be built from source)

- LACNIC/NIC Mexico validator (FORT)
  - https://fortproject.net/en/validator
  - https://nicmx.github.io/FORT-validator/
  - Packages available for Debian/Ubuntu, RHEL/CentOS & FreeBSD
  - (Can also be built from source)

RPKI Validator Caches (2)

- RPKI-client
  - https://www.rpki-client.org/
  - https://tracker.debian.org/pkg/rpki-client
  - RPKI repository query system (output for OpenBGPD, BIRD, json)
  - For OpenBSD, with ports for Debian/Ubuntu, RHEL/CentOS, FreeBSD, macOS
- StayRTR
  - https://github.com/bgp/stayrtr
  - https://tracker.debian.org/pkg/stayrtr
  - RPKI to Router protocol implementation (input JSON formatted VRP exports)
  - (hard fork of Cloudflare GoRTR)
  - Works on anything Go runs on (?)
- Note:
  - RPKI-client and StayRTR are used together

RPKI Validator Caches (3)

- RPKI-Prover
  - https://github.com/lolepezy/rpki-prover
- rpstir2
  - https://github.com/bgpsecurity/rpstir2

- No longer maintained:
  - Dragon Research Labs "rcynic"
  - Cloudflare validator (OctoRPKI/GoRTR)
    - StayRTR is a fork of GoRTR
  - RIPE NCC validator
    - Version 2 and 3

Installing a validator – Routinator

- If using Ubuntu/Debian, then simply use the package manager, as described:
  - https://github.com/NLnetLabs/routinator#quick-start-with-debian-and-ubuntu-packages
- In summary:
  - Get the NLnetLabs public key
  - Add the repo to the sources lists
  - Install routinator
  - Initialise
  - Run

```
philip@rpki:~$ wget -4 -qO- https://packages.nlnetlabs.nl/aptkey.asc | sudo apt-key add -
OK
philip@rpki:~$
```

```
philip@rpki:~$ sudo vi /etc/apt/sources.list.d/routinator-bionic.list
philip@rpki:~$ cat /etc/apt/sources.list.d/routinator-bionic.list
deb [arch=amd64] https://packages.nlnetlabs.nl/linux/ubuntu/ bionic main
philip@rpki:~$
```

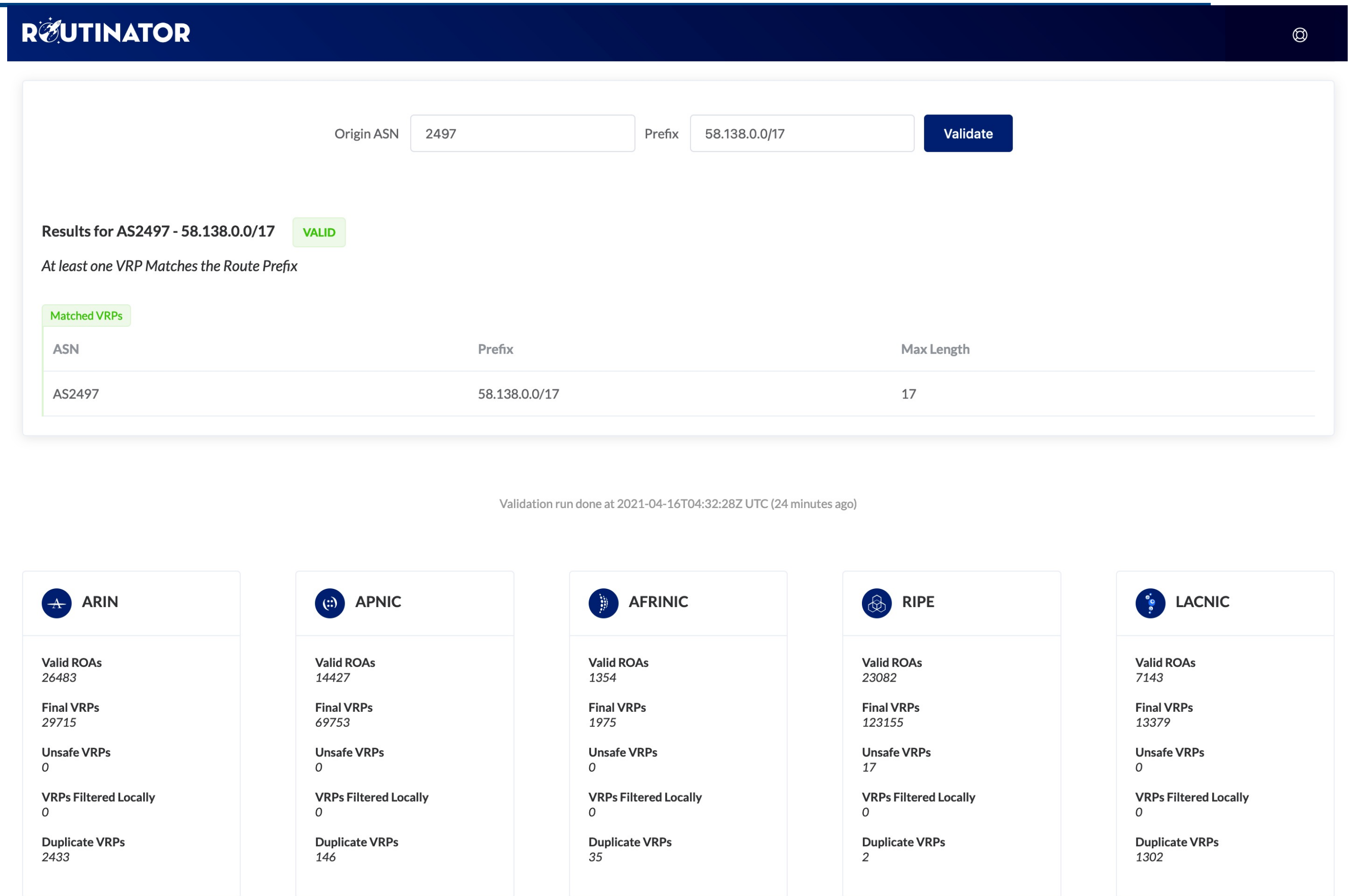
```
philip@rpki:~$ sudo apt install routinator
Reading package lists... Done
Use 'sudo apt autoremove' to remove it.
The following NEW packages will be installed:
  routinator
0 upgraded, 1 newly installed, 0 to remove and 0 not upgraded.
Need to get 1898 kB of archives.
Unpacking routinator (0.8.1-1bionic) ...
Setting up routinator (0.8.1-1bionic) ...
```

```
philip@rpki:~$ sudo routinator-init --accept-arin-rpa
Created local repository directory /var/lib/routinator/rpki-cache
Installed 5 TALs in /var/lib/routinator/tals
philip@rpki:~$ sudo systemctl enable --now routinator
philip@rpki:~$
```

Routinator 3000 web interface

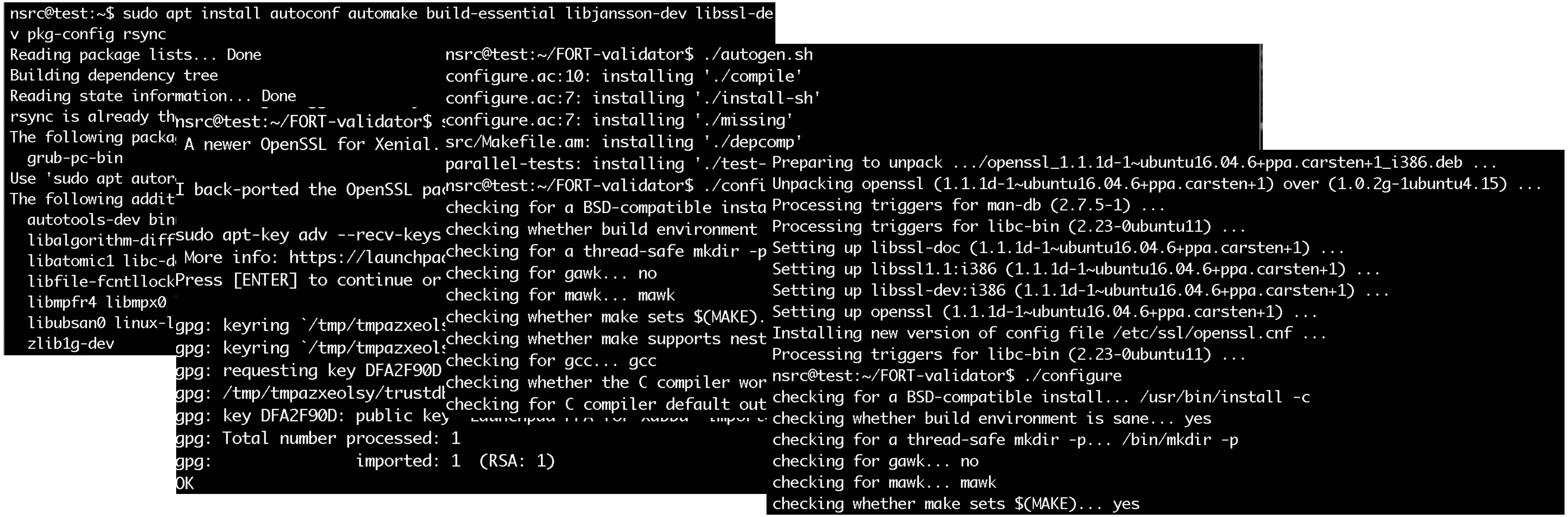
- User interface of Routinator accessed by enabling http option in the server configuration
  - Listens on port 8323

/etc/routinator/routinator.conf



Installing a validator – FORT

- If building from source, consult instructions at:
  - https://nicmx.github.io/FORT-validator/installation.html
  - Note: Needs OpenSSL >=1.1



RP Cache Deployment

- Network Operator design advice:
  - Deploy at least two Validator Caches
  - Geographically diverse
  - Perhaps two different implementations
    - For software independence
  - Implement on a Linux container so that the container can be moved between different server clusters as required
  - Configure validator to listen on both IPv4 and IPv6
    - Configure routers with both IPv4 and IPv6 validator connections
  - Securing the validator: Only permit routers running EBGP to have access to the validators

RP Cache Deployment: Open Questions

- Consider two different validator cache implementations
  - Gives software independence
  - What happens if the different cache implementations contain different VRPs?
  - Scenario 1:
    - Cache 1: route X is valid
    - Cache 2: route X is invalid
  - Scenario 2:
    - Cache 1: route X is valid
    - Cache 2: route X is NotFound
  - Answer: depends on router vendor implementation?!

Configure Router to Use Cache: Cisco IOS

- Point router to the local RPKI cache
  - Server listens on port 3323
  - Cache refreshed every 60 minutes (RFC8210 recommendation)
  - Example:

```
router bgp 64512
 bgp rpki server tcp 10.0.0.3 port 3323 refresh 3600
```

  - Once the router's RPKI table is populated, router indicates validation state in the BGP table

Cisco IOS status commands

- `show ip bgp rpki servers`
  - Displays the connection status to the RPKI caches
- `show ip bgp rpki table`
  - Shows the VRPs (validated ROA payloads)
- `show ip bgp`
  - Shows the BGP table with status indication next to the prefix
- `show ip bgp | i ^V`
  - Shows the status ”valid” prefixes in the BGP table

Configure Router to Use Cache: JunOS

1. Connect to validation cache:

```
routing-options {
  validation {
    group ISP {
      session 10.0.0.3;
      port 3323;
      refresh-time 600;
      hold-time 3600;
    }
  }
}
```

- (using same parameters as for the Cisco IOS example)

Configure Router to Use Cache: JunOS

2. Configure validation policies:

```
policy-options {
  policy-statement RPKI-validation {
    term VALID {
      from {
        protocol bgp;
        validation-database valid;
      }
      then {
        validation-state valid;
        next policy;
      }
    }
    term INVALID {
      from {
        protocol bgp;
        validation-database invalid;
      }
      then {
        validation-state invalid;
        next policy;
      }
    }
```

```
(continued)...

    term UNKNOWN {
      from {
        protocol bgp;
        validation-database unknown;
      }
      then {
        validation-state unknown;
        next policy;
      }
    }
  }
}
```

Configure Router to Use Cache: JunOS

3. Apply policy to eBGP session:

```
protocols {
  bgp {
    group EBGP {
      type external;
      local-address 10.0.1.1;
      neighbor 10.1.15.1 {
        description ”ISP Upstream";
        import [ RPKI-validation Upstream-in ];
        export LocalAS-out;
        peer-as 64511;
      }
    }
  }
}
```

- Note that policy options *Upstream-in* and *LocalAS-out* are the typical inbound and outbound filters needed for an eBGP session

JunOS status commands

- `show validation session detail`
  - Display the details of the connection to the RPKI caches
- `show validation replication database`
  - Shows the VRPs (validated ROA payloads)
- `show route protocol bgp`
  - Shows the BGP table with status indication next to the prefix

  `show route protocol bgp validation-state valid`
  - Shows the status ”valid” prefixes in the BGP table

Configure Router to Use Cache: FRrouting

- Point router to the local RPKI cache
  - Server listens on port 3323
  - Cache refreshed every 60 minutes (RFC8210 recommendation)
  - Example:

```
rpki
  rpki polling_period 3600
  rpki cache 10.0.0.3 3323 preference 1
  rpki cache 10.0.1.2 3323 preference 2
exit
```

  - Two caches specified for redundancy

FRrouting status commands

- `show rpki cache-connection`
  - Displays the connection status to the RPKI caches
- `show rpki prefix-table`
  - Shows the VRPs (validated ROA payloads)
- `show ip bgp`
  - Shows the BGP table
- `show ip bgp rpki valid`
  - Shows the status ”valid” prefixes in the BGP table
  - (There are also options for “invalid” and “notfound”)

Configure Router to Use Cache: BIRD v2

- Point BIRD to the local RPKI cache
  - Server listens on port 3323
  - Cache refreshed every 60 minutes (RFC8210 recommendation)
  - Two caches specified for redundancy

```
roa4 table r4;
roa6 table r6;

protocol rpki validator1 {
    roa4 { table r4; };
    roa6 { table r6; };
    remote 10.0.0.3 port 3323;
    retry 300;
}

protocol rpki validator2 {
    roa4 { table r4; };
    roa6 { table r6; };
    remote 10.0.1.2 port 3323;
    retry 300;
}
```

BIRD v2 status commands

- `show protocols validator1`
  - Displays the connection status to the RPKI cache "*validator1*"
- `show route table r4`
  - Shows the IPv4 VRPs (validated ROA payloads)

  `show route table r6`
  - Shows the IPv6 VRPs (validated ROA payloads)
- `show route protocol <name>`
  - Shows the BGP table

Implementation notes

- Cisco IOS/IOS-XE
  - Invalid prefixes are dropped by default
    - The operator does not need to define a policy based on validation state
  - Prefixes originated locally into IBGP are automatically marked as Valid
    - There is no check against the cached validation table
    - Allows operator to originate non-signed address blocks or other entity address space inside their own IBGP
- JunOS
  - Complete separation between validation table and what happens in BGP
    - There has to be a specific policy statement for any action based on validation state

Implementation notes

- Cisco IOS/IOS-XE/IOS-XR
  - Every VRP change causes a route-refresh with its BGP neighbours
    - Even though VRP change only affects valid/invalid/notfound status
  - Big impact for BGP sessions carrying a large or the full BGP table
    - Especially for BGP peers with weak control planes!
  - Transit providers need to be cautious:
    - BGP customer doing ROV on Cisco router will cause significant impact on the Access Router CPU
  - Cisco's recommended workaround:
    - Turn on "Soft Reconfiguration"
    - Which has memory implications, and blocks access to the route refresh CLI
  - Summary: think carefully about using Cisco routers for Route Origin Validation

Implementation notes

- Other router implementations
  - Most modern implementations save the incoming BGP table prior to policy application (ADJ-RIB-IN)
  - Changes in VRPs are applied to this stored BGP table
  - Similar behaviour to Cisco's soft-reconfiguration

- NB: It's important not to rely on Route Refresh to implement VRP changes
  - More and more frequent changes cause more and more refresh requests to peers, consuming peer CPU resources – potentially a denial of service attack on the peer
  - Recommended reading:
    - https://datatracker.ietf.org/doc/draft-ymbk-sidrops-rov-no-rr/

Implementation notes

- What happens when router cannot contact any validator cache?
  - Cisco IOS/IOS-XE – empties the VRP table within 5 minutes
  - Juniper & Nokia – keeps VRPs until their preconfigured expiry (default 60 minutes)
  - Other vendors – behaviour untested
- Design advice:
  - It is important to ensure that EBGP speaking routers can always remain connected to a validator cache
    - **Minimum of two independent caches recommended!**

Check Server

```
lg-01-jnb.za>sh ip bgp rpki servers
BGP SOVC neighbor is 105.16.112.2/43779 connected to port 43779
Flags 64, Refresh time is 300, Serial number is 1463607299
InQ has 0 messages, OutQ has 0 messages, formatted msg 493
Session IO flags 3, Session flags 4008
 Neighbor Statistics:
  Prefixes 25880
  Connection attempts: 44691
  Connection failures: 351
  Errors sent: 35
  Errors received: 0

Connection state is ESTAB, I/O status: 1, unread input bytes: 0
Connection is ECN Disabled
Mininum incoming TTL 0, Outgoing TTL 255
Local host: 105.22.32.2, Local port: 27575
Foreign host: 105.16.112.2, Foreign port: 43779
Connection tableid (VRF): 0
```

Courtesy of SEACOM: http://as37100.net

Check Server

```
philip@DREN-THIMPHU-BR> show validation session detail
Session 103.197.176.141, State: up, Session index: 2
  Group: DrukREN, Preference: 100
  Local IPv4 address: 103.197.176.5, Port: 3323
  Refresh time: 600s
  Hold time: 1800s
  Record Life time: 3600s
  Serial (Full Update): 0
  Serial (Incremental Update): 1
    Session flaps: 1
    Session uptime: 00:19:11
    Last PDU received: 00:00:34
    IPv4 prefix count: 94329
    IPv6 prefix count: 15992
```

Courtesy of DrukREN, Bhutan

RPKI Table (IPv4) – October 2021

```
217259 BGP sovc network entries using 34761440 bytes of memory
239398 BGP sovc record entries using 7660736 bytes of memory

Network              Maxlen   Origin-AS   Source   Neighbor
1.0.0.0/24           24       13335       0        192.168.1.225/3323
1.0.4.0/24           24       38803       0        192.168.1.225/3323
1.0.4.0/22           22       38803       0        192.168.1.225/3323
1.0.5.0/24           24       38803       0        192.168.1.225/3323
1.0.6.0/24           24       38803       0        192.168.1.225/3323
1.0.7.0/24           24       38803       0        192.168.1.225/3323
1.1.1.0/24           24       13335       0        192.168.1.225/3323
1.1.4.0/22           22       4134        0        192.168.1.225/3323
1.1.16.0/20          20       4134        0        192.168.1.225/3323
1.2.9.0/24           24       4134        0        192.168.1.225/3323
1.2.10.0/24          24       4134        0        192.168.1.225/3323
1.2.11.0/24          24       4134        0        192.168.1.225/3323
1.2.12.0/22          22       4134        0        192.168.1.225/3323
1.3.0.0/16           16       4134        0        192.168.1.225/3323
1.6.0.0/22           24       9583        0        192.168.1.225/3323
1.6.4.0/22           24       9583        0        192.168.1.225/3323
```

RPKI Table (IPv6) – October 2021

```
43391 BGP sovc network entries using 7983944 bytes of memory
46341 BGP sovc record entries using 1482912 bytes of memory

Network                Maxlen  Origin-AS  Source  Neighbor
2001:200::/32          32      2500       0       192.168.1.225/3323
2001:200:136::/48      48      9367       0       192.168.1.225/3323
2001:200:1BA::/48      48      24047      0       192.168.1.225/3323
2001:200:900::/40      40      7660       0       192.168.1.225/3323
2001:200:E00::/40      40      4690       0       192.168.1.225/3323
2001:200:8000::/35     35      4690       0       192.168.1.225/3323
2001:200:C000::/35     35      23634      0       192.168.1.225/3323
2001:200:E000::/35     35      7660       0       192.168.1.225/3323
2001:218:3002::/48     48      1613       0       192.168.1.225/3323
2001:240::/32          32      2497       0       192.168.1.225/3323
2001:260::/32          48      2518       0       192.168.1.225/3323
2001:288::/32          32      1659       0       192.168.1.225/3323
2001:2F0::/32          128     7514       0       192.168.1.225/3323
2001:300::/32          32      2497       0       192.168.1.225/3323
2001:360::/32          32      135887     0       192.168.1.225/3323
2001:360:12::/48       48      135887     0       192.168.1.225/3323
```

BGP Table (IPv4)

```
RPKI validation codes: V valid, I invalid, N Not found

Network          Metric LocPrf Path
N*>  1.0.4.0/24       0        37100 6939 4637 1221 38803 56203 i
N*>  1.0.5.0/24       0        37100 6939 4637 1221 38803 56203 i
...
V*>  1.9.0.0/16       0        37100 4788 i
N*>  1.10.8.0/24      0        37100 10026 18046 17408 58730 i
N*>  1.10.64.0/24     0        37100 6453 3491 133741 i
...
V*>  1.37.0.0/16      0        37100 4766 4775 i
N*>  1.38.0.0/23      0        37100 6453 1273 55410 38266 i
N*>  1.38.0.0/17      0        37100 6453 1273 55410 38266 {38266} i
...
I*   5.8.240.0/23     0        37100 44217 3178 i
I*   5.8.241.0/24     0        37100 44217 3178 i
I*   5.8.242.0/23     0        37100 44217 3178 i
I*   5.8.244.0/23     0        37100 44217 3178 i
...
```

Courtesy of SEACOM: http://as37100.net

BGP Table (IPv6)

```
RPKI validation codes: V valid, I invalid, N Not found

Network                  Metric LocPrf Path
N*>  2001::/32              0          37100 6939 i
N*   2001:4:112::/48        0          37100 112 i
...
V*>  2001:240::/32          0           37100 2497 i
N*>  2001:250::/48          0           37100 6939 23911 45
N*>  2001:250::/32          0           37100 6939 23911 23910 i
...
V*>  2001:348::/32          0           37100 2497 7679 i
N*>  2001:350::/32          0           37100 2497 7671 i
N*>  2001:358::/32          0           37100 2497 4680 i
...
I*   2001:1218:101::/48     0           37100 6453 8151 278 i
I*   2001:1218:104::/48     0           37100 6453 8151 278 i
N*   2001:1221::/48         0           37100 2914 8151 28496 i
N*>  2001:1228::/32         0           37100 174 18592 i
...
```

Courtesy of SEACOM: http://as37100.net

RPKI BGP State: Valid

```
BGP routing table entry for 2001:240::/32, version 109576927
Paths: (2 available, best #2, table default)
  Not advertised to any peer
  Refresh Epoch 1
  37100 2497
    2C0F:FEB0:11:2::1 (FE80::2A8A:1C00:1560:5BC0) from
                                  2C0F:FEB0:11:2::1 (105.16.0.131)
      Origin IGP, metric 0, localpref 100, valid, external, best
      Community: 37100:2 37100:22000 37100:22004 37100:22060
      path 0828B828 RPKI State valid
      rx pathid: 0, tx pathid: 0x0
```

Courtesy of SEACOM: http://as37100.net

RPKI BGP State: Invalid

```
BGP routing table entry for 2001:1218:101::/48, version 149538323
Paths: (2 available, no best path)
  Not advertised to any peer
  Refresh Epoch 1
  37100 6453 8151 278
    2C0F:FEB0:B:3::1 (FE80::86B5:9C00:15F5:7C00) from
                                                  2C0F:FEB0:B:3::1 (105.16.0.162)
      Origin IGP, metric 0, localpref 100, valid, external
      Community: 37100:1 37100:12
      path 0DA7D4FC RPKI State invalid
      rx pathid: 0, tx pathid: 0
```


Courtesy of SEACOM: http://as37100.net

RPKI BGP State: Not Found

```
BGP routing table entry for 2001:200::/32, version 124240929
Paths: (2 available, best #2, table default)
  Not advertised to any peer
  Refresh Epoch 1
  37100 2914 2500
    2C0F:FEB0:11:2::1 (FE80::2A8A:1C00:1560:5BC0) from
                                        2C0F:FEB0:11:2::1 (105.16.0.131)
      Origin IGP, metric 0, localpref 100, valid, external, best
      Community: 37100:1 37100:13
      path 19D90E68 RPKI State not found
      rx pathid: 0, tx pathid: 0x0
```


Courtesy of SEACOM: http://as37100.net

Using RPKI

- Network operators can make decisions based on RPKI state:
  - Invalid – discard the prefix – many do this now!
  - NotFound – let it through (maybe low local preference)
  - Valid – let it through (high local preference)
- Some operators even considering making "Not Found" a discard event
  - But then Internet IPv4 BGP table would shrink to about 220000 prefixes and the IPv6 BGP table would shrink to about 43000 prefixes!

Deploying RPKI within an AS

- For fully supported Route Origin Validation across the network:
  - All EBGP speaking routers need talk with a validator
    - Supporting ROV means dropping **invalid**s as they arrive in the network
    - EBGP speaking routers are part of the operator IBGP mesh
  - IBGP speaking routers do not need to talk with a validator
    - Only **valid** and **NotFound** prefixes will be distributed from the EBGP speaking routers
    - The validation table is not distributed from router to router
- Remember:
  - Cisco IOS/IOS-XE drops **invalid**s by default – to allow **invalid**s to be distributed by IBGP, use the per address-family command:

```
bgp bestpath prefix-validate allow-invalid
```

Propagating validation state

- RFC8097 describes the propagation of validation state between iBGP speakers
  - Defines an opaque extended BGP community

Extended Community	Meaning
0x4300:0:0	Valid
0x4300:0:1	NotFound
0x4300:0:2	Invalid

  - These extended communities can be used in IBGP to allow distribution of validation state along with the prefix if desired
  - On Cisco IOS/IOS-XE:

```
neighbor x.x.x.x announce rpki state
```

  - For JunOS, policy needs to be explicitly configured

Propagating validation state

- There are two important caveats when propagating validation state:
  - Interoperability – is the defined opaque extended community supported on all vendor equipment in a multi-vendor network?
    - Until recently JunOS would not allow the required opaque extended communities to be configured at the command line
  - Cisco IOS/IOS-XE behaviour:
    - Adds a step to the best path selection algorithm: checks validation state (***valid*** **preferred over** ***not found***) before checking local preference
      - This cannot be turned off 🤯🤬

JunOS: opaque extended community

- Supported only in most recent JunOS releases
  - Fixed from 17.4R3, 18.2R3, 18.4R2…

```
policy-options {
    community RPKI-VALID members 0x4300:0:0;
    community RPKI-UNKNOWN members 0x4300:0:1;
    community RPKI-INVALID members 0x4300:0:2;
}
```

JunOS: opaque extended community

- And we can now set policy to detect these communities being sent from Cisco IOS/IOS-XE routers
  - Under "policy-options":

```
policy-statement PEER-in {
    term VALID {
        from community RPKI-VALID;
        then {
            validation-state valid;
            next policy;
        }
    }
    term INVALID {
        from community RPKI-INVALID;
        then {
            validation-state invalid;
            next policy;
        }
    }
    term UNKNOWN {
        from community RPKI-UNKNOWN;
        then {
            validation-state unknown;
            next policy;
        }
    }
}
```

Propagating validation state: Cisco IOS

- Cisco IOS/IOS-XE behaviour – example:
  - Prefix learned via two paths via two separate EBGP speaking routers
  - Prefix and validation state distributed by IBGP to core router (route reflector):

```
     Network          Next Hop      Metric LocPrf Weight Path
V*>i 61.45.249.0/24   100.68.1.1         0     50      0 121 20 135534 i
N* i                  100.68.1.3         0    200      0 20 135534 i
V*>i 61.45.250.0/24   100.68.1.1         0     50      0 121 30 135535 i
N* i                  100.68.1.3         0    150      0 30 135535 i
V*>i 61.45.251.0/24   100.68.1.1         0     50      0 121 122 40 135536 i
N* i                  100.68.1.3         0    150      0 40 135536 i
```

  - One EBGP speaking router talks with validator
  - The other EBGP speaking router does not (due to error or design)
  - Core router best path selection prefers *valid* path over *not found* even if the latter has higher local preference

Propagating validation state: Cisco IOS

- Looking at the path detail:

```
BGP routing table entry for 61.45.249.0/24, version 32
BGP Bestpath: deterministic-med
Paths: (2 available, best #1, table default)
  Not advertised to any peer
  Refresh Epoch 1
  121 20 135534, (Received from a RR-client)
    100.68.1.1 (metric 2) from 100.68.1.1 (100.68.1.1)
      Origin IGP, metric 0, localpref 50, valid, internal, best
      Extended Community: 0x4300:0:0
      path 67A585D0 RPKI State valid
  Refresh Epoch 1
  20 135534, (Received from a RR-client)
    100.68.1.3 (metric 2) from 100.68.1.3 (100.68.1.3)
      Origin IGP, metric 0, localpref 200, valid, internal
      Community: 10:1100
      Extended Community: 0x4300:0:1
      path 67A58918 RPKI State not found
```

Note best path

Propagating validation state

- Consider carefully if this is desired
- Current standard practice is to:
  - EBGP speaking routers have session with two diverse/redundant validators
  - Check validation state on EBGP speaking routers
  - Drop invalids on EBGP speaking routers
  - Distribute remaining prefixes by IBGP
  - Avoid propagating validation state (at least in Cisco IOS)

    -or-

  - Make sure that EBGP speaking routers never lose their connectivity to validators

RPKI Summary

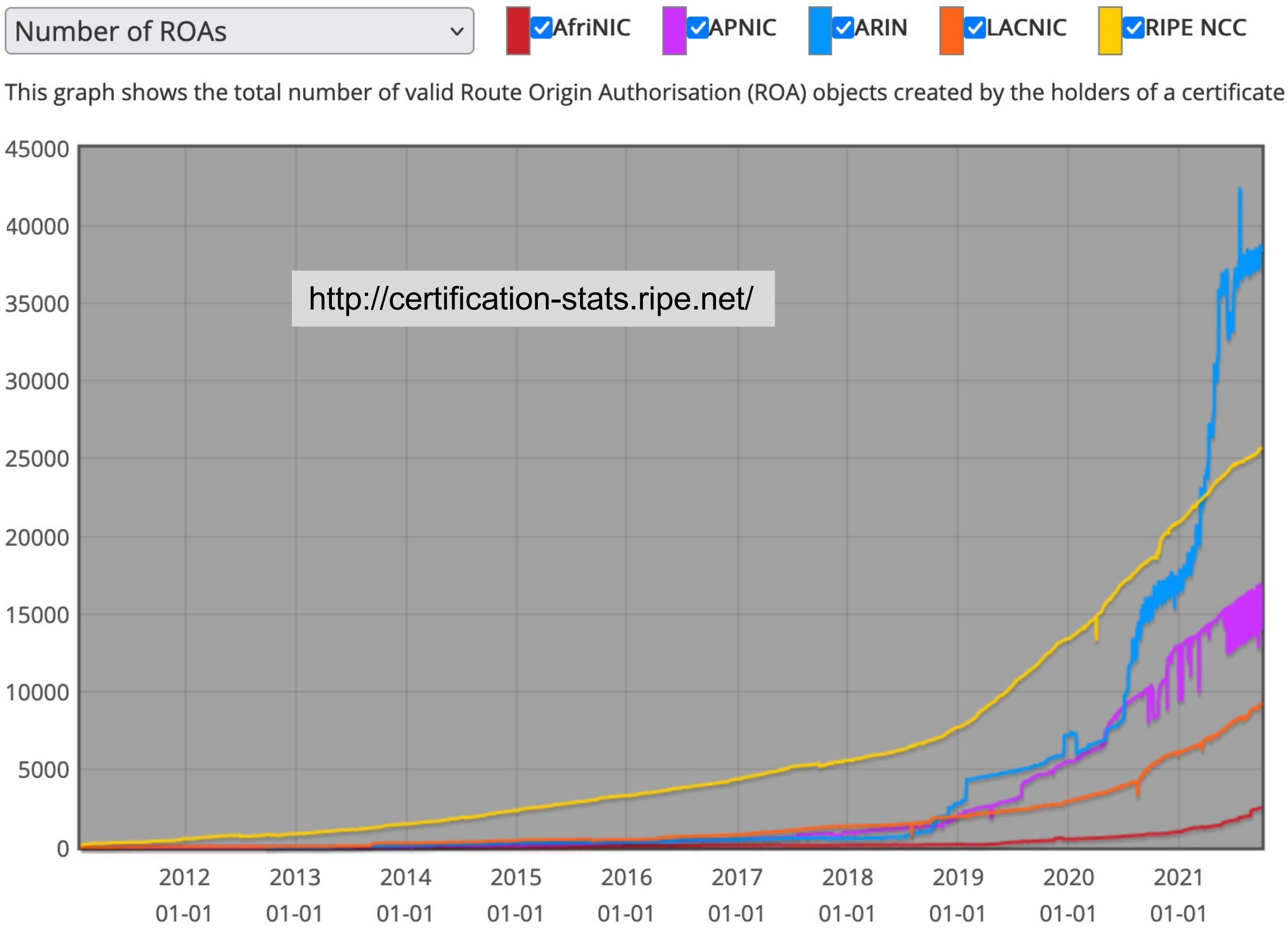
- All AS operators must consider deploying:
  - **Signing ROAs**
  - **Dropping Invalids** (ROV)
- An important step to securing the routing system
- Doesn't secure the path, but that's the next important hurdle to cross
- With origin validation, the opportunities for malicious or accidental mis-origination are considerably reduced
- FAQ:
  - https://nlnetlabs.nl/projects/rpki/faq/

Autonomous System Provider Authorisation

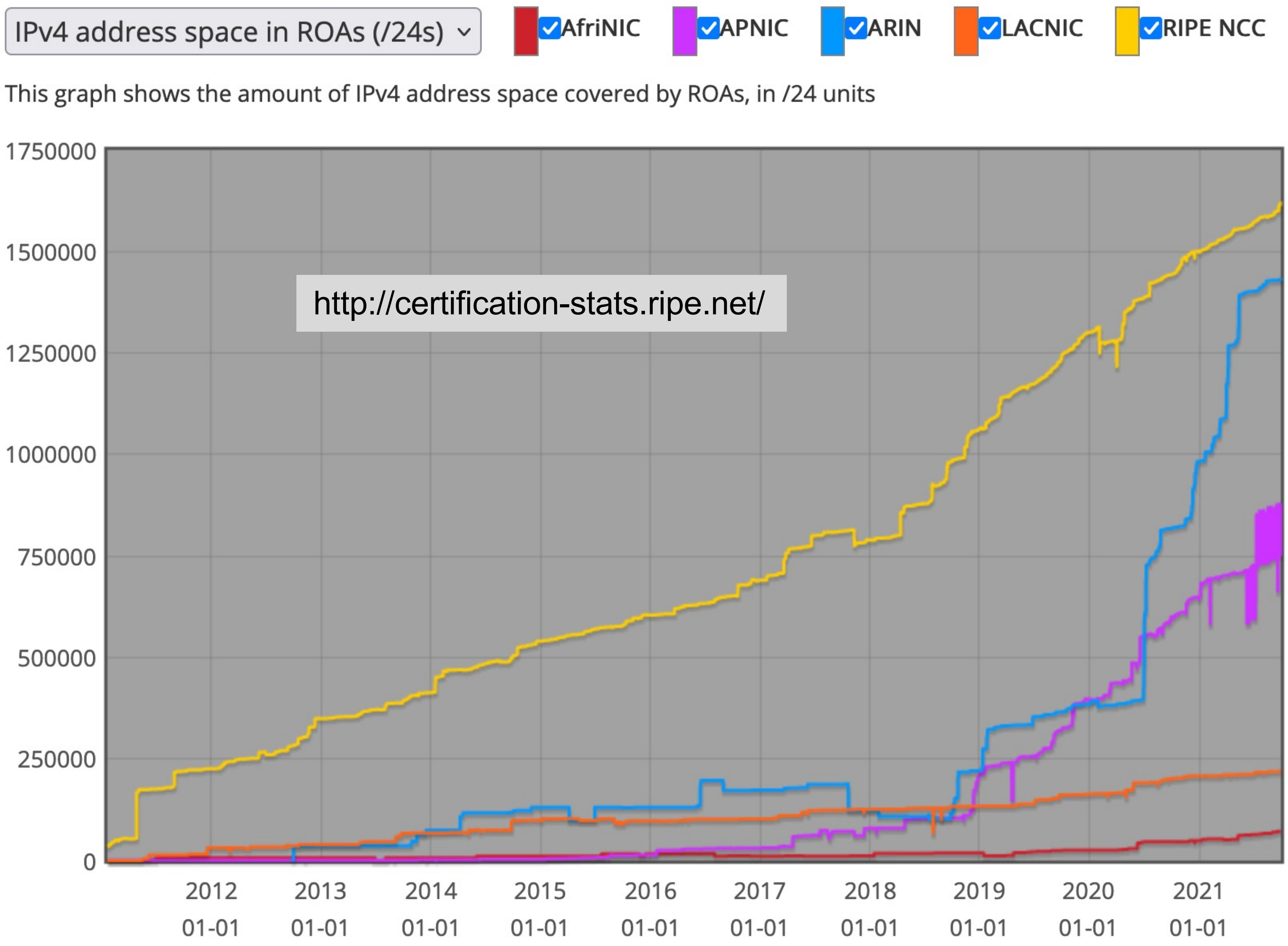
- ASPA is the next step after signing ROAs and implementing ROV
  - ASPA is a digitally signed object that binds, for a selected address family, a Set of Provider AS numbers to a Customer AS number (in terms of BGP announcements)
  - The object is signed by the holder of the Customer AS
    - The AS holder is signing who their adjacent ASes are
  - The ASPA record attests that the Customer AS has authorised the Set of Provider ASes to propagate the customer's IPv4/IPv6 announcements onwards
  - https://datatracker.ietf.org/doc/draft-ietf-sidrops-aspa-verification/

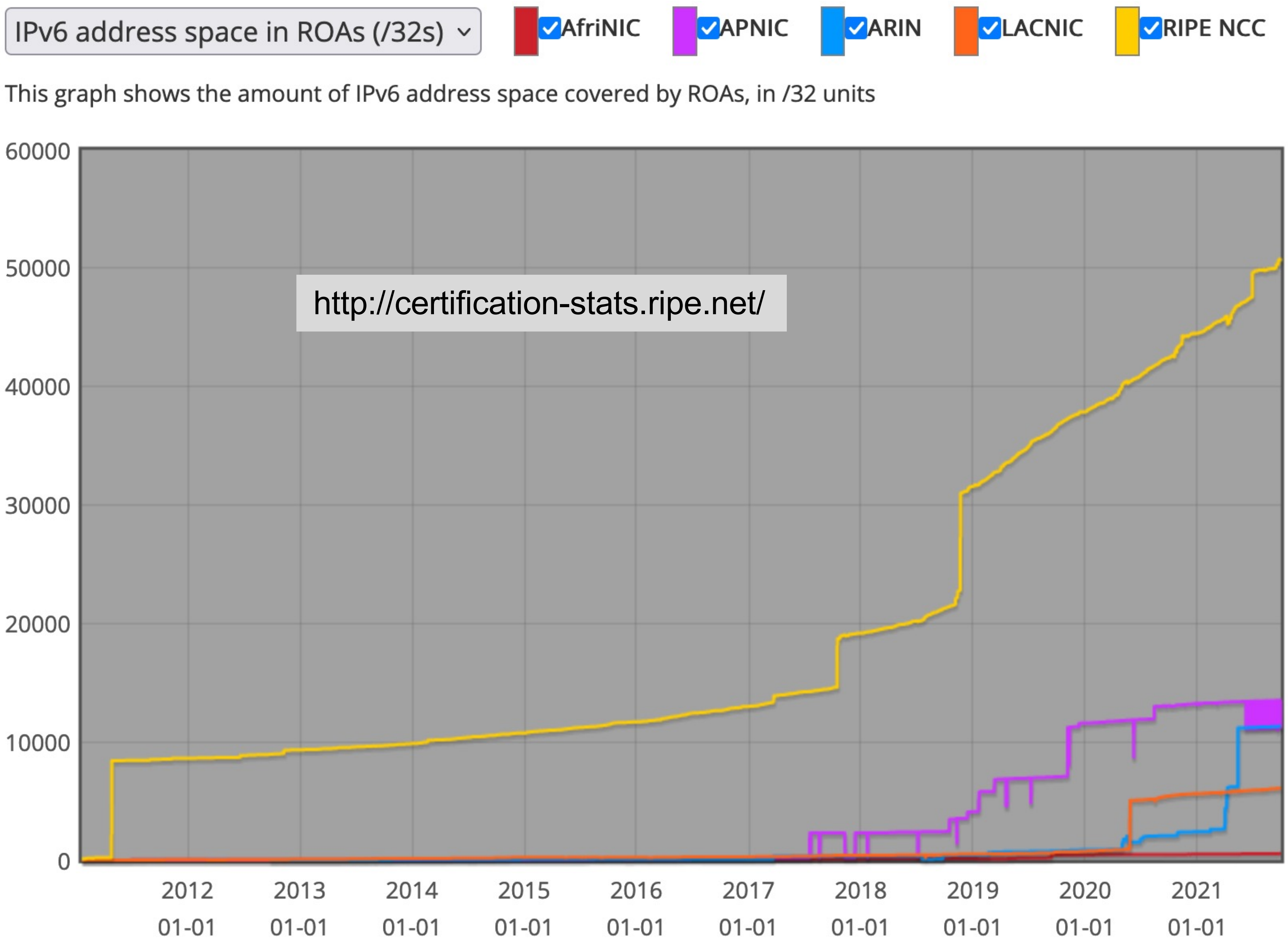
ASPA implementation

- Once the customer has signed their ASPA attestation:
  - The neighbour AS providers (relying party) need to have access to the complete set of cryptographically valid ASPAs
  - The relying party retrieves all cryptographically valid ASPAs for the customer AS
    - If none exist, then the outcome is "Unknown"
    - If the relying party's AS is included, the outcome is "Valid"
    - If the relying party's AS is NOT included, the outcome is "Invalid"
- ASPA is still in development:
  - Router OS support and validator implementations are still in the early stages
  - Discussion ongoing in IETF SIDR Ops Working Group



Number of ROAs
AfriNIC
APNIC
ARIN
LACNIC
RIPE NCC
This graph shows the total number of valid Route Origin Authorisation (ROA) objects created by the holders of a certificate
http://certification-stats.ripe.net/
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
2012 01-01
2013 01-01
2014 01-01
2015 01-01
2016 01-01
2017 01-01
2018 01-01
2019 01-01
2020 01-01
2021 01-01


IPv4 address space in ROAs (/24s)
AfriNIC
APNIC
ARIN
LACNIC
RIPE NCC
This graph shows the amount of IPv4 address space covered by ROAs, in /24 units
1750000
1500000
1250000
1000000
750000
500000
250000
0
http://certification-stats.ripe.net/
2012 01-01
2013 01-01
2014 01-01
2015 01-01
2016 01-01
2017 01-01
2018 01-01
2019 01-01
2020 01-01
2021 01-01



IPv6 address space in ROAs (/32s)
AfriNIC
APNIC
ARIN
LACNIC
RIPE NCC
This graph shows the amount of IPv6 address space covered by ROAs, in /32 units
60000
50000
40000
30000
20000
10000
0
2012 01-01
2013 01-01
2014 01-01
2015 01-01
2016 01-01
2017 01-01
2018 01-01
2019 01-01
2020 01-01
2021 01-01
http://certification-stats.ripe.net/

RPKI Deployment Status

- NIST keeps track of deployment status for research purposes:
  - https://rpki-monitor.antd.nist.gov/
- RIPE NCC statistics:
  - http://certification-stats.ripe.net/
- APNIC R&D ROA status:
  - RIPE NCC Validator running at APNIC
  - http://nong.rand.apnic.net:8080/roas

Major Operators deploying RPKI and ROV

- Telia

```
aut-num:        AS1299
org:            ORG-TCA23-RIPE
as-name:        TELIANET
descr:          Telia Carrier
<snip>
remarks:        AS1299 is matching RPKI validation state and reject
remarks:        invalid prefixes from peers, and are currently extending
remarks:        this to our customer connections.
remarks:
remarks:        Our looking-glass at https://lg.telia.net/ marks
remarks:        validation state for all prefixes.
remarks:
remarks:        Please review your registered ROAs to reduce number
remarks:        of invalid prefixes.
```

Major Operators deploying RPKI and ROV

- More and more operators are deploying RPKI and ROV
- Not just transit providers!
- But also:
  - Content providers
  - IXPs
  - R&E networks
  - Access providers

- Telia
- NTT
- Lumen (ex L3)
- HE
- GTT
- Workonline
- SEACOM
- Cloudflare
- AMS-IX
- LINX
- DE-CIX
- Terrehost
- Vocus
- Telstra
- REANNZ
- Cogent
- GR-IX
- Swisscom
- Netflix
- UAE-IX
- …

Routing Security

- Implement the recommendations in https://www.manrs.org
  1. Prevent propagation of incorrect routing information
     - Filter BGP peers, in & out!
  2. Prevent traffic with spoofed source addresses
     - BCP38 – Unicast Reverse Path Forwarding
  3. Facilitate communication between network operators
     - NOC to NOC Communication
     - Up-to-date details in Route and AS Objects, and PeeringDB
  4. Facilitate validation of routing information
     - Route Origin Authorisation using RPKI

MANRS

Summary

- Deploy RPKI
  - It is in the Internet’s best interest
- With wide deployment of RPKI it becomes possible to only allow validated prefix announcements into the Internet Routing System
  - Prevents mis-originations
  - Prevents prefix hijack
  - Makes the Internet infrastructure more reliable and more stable
  - Allows the next step: AS-PATH validation

BGP Origin Validation

ISP Workshops