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Proof of Transit
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Abstract

Several technologies such as traffic engineering, service function chaining, or policy based routing, are used to steer traffic through a specific, user-defined path. This document defines mechanisms to securely prove that traffic transited the defined path. The mechanisms allow to securely verify whether all packets traversed all those nodes of a given path that they are supposed to visit.

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1. Introduction

Several deployments use traffic engineering, policy routing, segment routing or Service Function Chaining (SFC) [RFC7665] to steer packets through a specific set of nodes. In certain cases regulatory obligations or a compliance policy require operators to prove that all packets that are supposed to follow a specific path are indeed being forwarded across and exact set of pre-determined nodes.

If a packet flow is supposed to go through a series of service functions or network nodes, it has to be proven that indeed all packets of the flow followed the path or service chain or collection of nodes specified by the policy. In case some packets of a flow weren't appropriately processed, a verification device should determine the policy violation and take corresponding actions corresponding to the policy (e.g., drop or redirect the packet, send an alert etc.). In today's deployments, the proof that a packet traversed a particular path or service chain is typically delivered in an indirect way: Service appliances and network forwarding are in different trust domains. Physical hand-off-points are defined between these trust domains (i.e. physical interfaces). Or in other terms, in the "network forwarding domain" things are wired up in a way that traffic is delivered to the ingress interface of a service appliance and received back from an egress interface of a service appliance. This "wiring" is verified and then trusted upon. The evolution to Network Function Virtualization (NFV) and modern service chaining concepts (using technologies such as LISP, NSH, Segment Routing (SR), etc.) blurs the line between the different trust domains, because the hand-off-points are no longer clearly defined physical interfaces, but are virtual interfaces. As a consequence, different trust layers should not to be mixed in the same device. For an NFV scenario a different type of proof is required. Offering a proof that a packet indeed traversed a specific set of service functions or nodes allows operators to evolve from the above described indirect methods of proving that packets visit a predetermined set of nodes.

The solution approach presented in this document is based on a small portion of operational data added to every packet. This "in-band" operational data is also referred to as "proof of transit data", or POT data. The POT data is updated at every required node and is used to verify whether a packet traversed all required nodes. A particular set of nodes "to be verified" is either described by a set of secret keys, or a set of shares of a single secret. Nodes on the

path retrieve their individual keys or shares of a key (using for e.g., Shamir's Secret Sharing scheme) from a central controller. The complete key set is only known to the controller and a verifier node, which is typically the ultimate node on a path that performs verification. Each node in the path uses its secret or share of the secret to update the POT data of the packets as the packets pass through the node. When the verifier receives a packet, it uses its key(s) along with data found in the packet to validate whether the packet traversed the path correctly.

2. Conventions

Abbreviations used in this document:

MTU: Maximum Transmit Unit

SR: Segment Routing

NSH: Network Service Header

SFC: Service Function Chain

POT: Proof of Transit

POT-profile: Proof of Transit Profile that has the necessary data for nodes to participate in proof of transit

3. Proof of Transit

This section discusses methods and algorithms to provide for a "proof of transit" for packets traversing a specific path. A path which is to be verified consists of a set of nodes. Transit of the data packets through those nodes is to be proven. Besides the nodes, the setup also includes a Controller that creates secrets and secrets shares and configures the nodes for POT operations.

The methods how traffic is identified and associated to a specific path is outside the scope of this document. Identification could be done using a filter (e.g., 5-tupel classifier), or an identifier which is already present in the packet (e.g., path or service identifier, flow-label, etc.).

The solution approach is detailed in two steps. Initially the concept of the approach is explained. This concept is then further refined to make it operationally feasible.

3.1. Basic Idea

The method relies on adding POT data to all packets that traverse a path. The added POT data allows a verifying node (egress node) to check whether a packet traversed the identified set of nodes on a path correctly or not. Security mechanisms are natively built into the generation of the POT data to protect against misuse (i.e. configuration mistakes, malicious administrators playing tricks with routing, capturing, spoofing and replaying packets). The mechanism for POT leverages "Shamir's secret sharing scheme" [SSS].

Shamir's secret sharing base idea: A polynomial (represented by its co-efficients) is chosen as a secret by the controller. A polynomial represents a curve. A set of well defined points on the curve are needed to construct the polynomial. Each point of the polynomial is called "share" of the secret. A single secret is associated with a particular set of nodes, which typically represent the path, to be verified. Shares of the single secret (i.e., points on the curve) are securely distributed from a Controller to the network nodes. Nodes use their respective share to update a cumulative value in the POT data of each packet. Only a verifying node has access to the complete secret. The verifying node validates the correctness of the received POT data by reconstructing the curve.

The polynomial cannot be constructed if any of the points are missed or tampered. Per Shamir's Secret Sharing Scheme, any lesser points means one or more nodes are missed. Details of the precise configuration needed for achieving security are discussed further below.

While applicable in theory, a vanilla approach based on Shamir's secret sharing could be easily attacked. If the same polynomial is reused for every packet for a path a passive attacker could reuse the value. As a consequence, one could consider creating a different polynomial per packet. Such an approach would be operationally complex. It would be complex to configure and recycle so many curves and their respective points for each node. Rather than using a single polynomial, two polynomials are used for the solution approach: A secret polynomial which is kept constant, and a per-packet polynomial which is public. Operations are performed on the sum of those two polynomials - creating a third polynomial which is secret and per packet.

3.2. Solution Approach

Solution approach: The overall algorithm uses two polynomials: POLY-1 and POLY-2. POLY-1 is secret and constant. Each node gets a point on POLY-1 at setup-time and keeps it secret. POLY-2 is public,

random and per packet. Each node generates a point on POLY-2 each time a packet crosses it. Each node then calculates (point on POLY-1 + point on POLY-2) to get a (point on POLY-3) and passes it to verifier by adding it to each packet. The verifier constructs POLY-3 from the points given by all the nodes and cross checks whether POLY-3 = POLY-1 + POLY-2. Only the verifier knows POLY-1. The solution leverages finite field arithmetic in a field of size "prime number".

Detailed algorithms are discussed next. A simple example is discussed in Section 3.3.

3.2.1. Setup

A controller generates a first polynomial (POLY-1) of degree k and k+1 points on the polynomial. The constant coefficient of POLY-1 is considered the SECRET. The non-constant coefficients are used to generate the Lagrange Polynomial Constants (LPC). Each of the k nodes (including verifier) are assigned a point on the polynomial i.e., shares of the SECRET. The verifier is configured with the SECRET. The Controller also generates coefficients (except the constant coefficient, called "RND", which is changed on a per packet basis) of a second polynomial POLY-2 of the same degree. Each node is configured with the LPC of POLY-2. Note that POLY-2 is public.

3.2.2. In Transit

For each packet, the source node generates a random number (RND). It is considered as the constant coefficient for POLY-2. A cumulative value (CML) is initialized to 0. Both RND, CML are carried as within the packet POT data. As the packet visits each node, the RND is retrieved from the packet and the respective share of POLY-2 is calculated. Each node calculates (Share(POLY-1)+Share(POLY-2)) and CML is updated with this sum. This step is performed by each node until the packet completes the path. The verifier also performs the step with its respective share.

3.2.3. Verification

The verifier cross checks whether CML = SECRET + RND. If this matches then the packet traversed the specified set of nodes in the path. This is due to the additive homomorphic property of Shamir's Secret Sharing scheme.

3.3. Example for Illustration

This section shows a simple example to illustrate step by step the approach described above.

3.3.1. Basic Version

Assumption: We like to verify that packets pass through 3 nodes. Consequently we need a polynomial of degree 2.

Choices: Prime = 53. POLY-1(x) = (3x^2 + 3x + 10) mod 53. The secret to be re-constructed is the constant coefficient of POLY-1, i.e., SECRET=10. It is important to note that all operations are done over a finite field (i.e., modulo prime).

3.3.1.1. Secret Shares

The shares of the secret are the points on POLY-1 chosen for the 3 nodes. Here we use x0=2, x1=4, x2=5.

POLY-1(2) = 28 => (x0,y0) = (2,28)

POLY-1(4) = 17 => (x1,y1) = (4,17)

POLY-1(5) = 47 => (x2,y2) = (5,47)

The three points above are the points on the curve which are considered the shares of the secret. They are assigned to three nodes respectively and are kept secret.

3.3.1.2. Lagrange Polynomials

Lagrange basis polynomials (or Lagrange polynomials) are used for polynomial interpolation. For a given set of points on the curve Lagrange polynomials (as defined below) are used to reconstruct the curve and thus reconstruct the complete secret.

l0(x) = (((x-x1)/(x0-x1))*((x-x2)/x0-x2))) mod 53 =
(((x-4)/(2-4))*((x-5)/2-5))) mod 53 =
(10/3 - 3x/2 + (1/6)x^2) mod 53

l1(x) = (((x-x0)/(x1-x0))*((x-x2)/x1-x2))) mod 53 =
(-5 + 7x/2 - (1/2)x^2) mod 53

l2(x) = (((x-x0)/(x2-x0))*((x-x1)/x2-x1))) mod 53 =
(8/3 - 2 + (1/3)x^2) mod 53

3.3.1.3. LPC Computation

Since x0=2, x1=4, x2=5 are chosen points. Given that computations are done over a finite arithmetic field ("modulo a prime number"), the Lagrange basis polynomial constants (LPC) are computed modulo 53. The Lagrange polynomial constant (LPC) would be 10/3 , -5 , 8/3.

LPC(x0) = (10/3) mod 53 = 21

LPC(x1) = (-5) mod 53 = 48

LPC(x2) = (8/3) mod 53 = 38

For a general way to compute the modular multiplicative inverse, see e.g., the Euclidean algorithm.

3.3.1.4. Reconstruction

Reconstruction of the polynomial is well defined as

POLY1(x) = l0(x)*y0 + l1(x)*y1 + l2(x)*y2.

Subsequently, the SECRET, which is the constant coefficient of POLY1(x) can be computed as below

SECRET = (y0*LPC(l0)+y1*LPC(l1)+y2*LPC(l2)) mod 53.

The secret can be easily reconstructed using the y-values and the LPC:

SECRET = (y0*LPC(l0) + y1*LPC(l1) + y2*LPC(l2)) mod 53 = mod (28 * 21 + 17 * 48 + 47 * 38) mod 53 = 3190 mod 53 = 10.

One observes that the secret reconstruction can easily be performed cumulatively hop by hop. CML represents the cumulative value. It is the POT data in the packet that is updated at each hop with the node's respective (yi*LPC(i)), where i is their respective value.

3.3.1.5. Verification

Upon completion of the path, the resulting CML is retrieved by the verifier from the packet POT data. Recall that verifier is preconfigured with the original SECRET. It is cross checked with the CML by the verifier. Subsequent actions based on the verification failing or succeeding could be taken as per the configured policies.

3.3.2. Enhanced Version

As observed previously, the vanilla algorithm that involves a single secret polynomial is not secure. We enhance the solution with usage of a random second polynomial chosen per packet.

3.3.2.1. Random Polynomial

Let the second polynomial POLY-2 be (RND + 7x + 10 x^2). RND is a random number and is generated for each packet. Note that POLY-2 is public and need not be kept secret. The nodes can be pre-configured with the non-constant coefficients (for example, 7 and 10 in this case could be configured through the Controller on each node).

3.3.2.2. Reconstruction

Recall that each node is preconfigured with their respective Share(POLY-1). Each node calculates its respective Share(POLY-2) using the RND value retrieved from the packet. The CML reconstruction is enhanced as below. At every node, CML is updated as

CML = CML+(((Share(POLY-1)+ Share(POLY-2)) * LPC) mod Prime.

Lets observe the packet level transformations in detail. For the example packet here, let the value RND be 45. Thus POLY-2 would be (45 + 7x + 10x^2).

The shares that could be generated are (2,46), (4,21), (5,12).

At source: The fields RND = 45. CML = 0.

At node-1 (x0): Respective share of POLY-2 is generated i.e (2,46) because share index of node-1 is 2.

CML = 0 + ((28 + 46)* 21) mod 53 = 17.

At node-2 (x1): Respective share of POLY-2 is generated i.e (4,21) because share index of node-2 is 4.

CML = 17 + ((17 + 21)*48) mod 53 = 17 + 22 = 39.

At node-3 (x2), which is also the verifier: The respective share of POLY-2 is generated i.e (5,12) because the share index of the verifier is 12.

CML = 39 + ((47 + 12)*38) mod 53 = 39 + 16 = 55 mod 53 = 2

The verification using CML is discussed in next section.

3.3.2.3. Verification

As shown in the above example, for final verification, the verifier compares:

VERIFY = (SECRET + RND) mod Prime, with Prime = 53 here.

VERIFY = (RND-1 + RND-2) mod Prime = (10 + 45) mod 53 = 2.

Since VERIFY = CML the packet is proven to have gone through nodes 1, 2, and 3.

3.4. Operational Aspects

To operationalize this scheme, a central controller is used to generate the necessary polynomials, the secret share per node, the prime number, etc. and distributing the data to the nodes participating in proof of transit. The identified node that performs the verification is provided with the verification key. The information provided from the Controller to each of the nodes participating in proof of transit is referred to as a proof of transit profile (POT-profile). Also note that the set of nodes for which the transit has to be proven are typically associated to a different trust domain than the verifier. Note that building the trust relationship between the Controller and the nodes is outside the scope of this document. Techniques such as those described in [I-D.ietf-anima-autonomic-control-plane] might be applied.

To optimize the overall data amount of exchanged and the processing at the nodes the following optimizations are performed:

1. The points (x,y) for each of the nodes on the public and private polynomials are picked such that the x component of the points match. This lends to the LPC values which are used to calculate the cumulative value CML to be constant. Note that the LPC are only depending on the x components. The can be computed at the controller and communicated to the nodes. Otherwise, one would need to distributed the x components to all the nodes.

2. A pre-evaluated portion of the public polynomial for each of the nodes is calculated and added to the POT-profile. Without this all the coefficients of the public polynomial had to be added to the POT profile and each node had to evaluate them.

3. To provide flexibility on the size of the cumulative and random numbers carried in the POT data a field to indicate this is shared and interpreted at the nodes.

4. Sizing the Data for Proof of Transit

Proof of transit requires transport of two data records in every packet that should be verified:

1. RND: Random number (the constant coefficient of public polynomial)

2. CML: Cumulative

The size of the data records determines how often a new set of polynomials would need to be created. At maximum, the largest RND number that can be represented with a given number of bits determines the number of unique polynomials POLY-2 that can be created. The table below shows the maximum interval for how long a single set of polynomials could last for a variety of bit rates and RND sizes: When choosing 64 bits for RND and CML data records, the time between a renewal of secrets could be as long as 3,100 years, even when running at 100 Gbps.

Transfer rate	Secret/RND size	Max # of packets	Time RND lasts
1 Gbps	64	2^64 = approx. 2*10^19	approx. 310,000 years
10 Gbps	64	2^64 = approx. 2*10^19	approx. 31,000 years
100 Gbps	64	2^64 = approx. 2*10^19	approx. 3,100 years
1 Gbps	32	2^32 = approx. 4*10^9	2,200 seconds
10 Gbps	32	2^32 = approx. 4*10^9	220 seconds
100 Gbps	32	2^32 = approx. 4*10^9	22 seconds

Table assumes 64 octet packets

Table 1: Proof of transit data sizing

5. Node Configuration

A POT system consists of a number of nodes that participate in POT and a Controller, which serves as a control and configuration entity. The Controller is to create the required parameters (polynomials, prime number, etc.) and communicate those to the nodes. The sum of all parameters for a specific node is referred to as "POT-profile". This document does not define a specific protocol to be used between Controller and nodes. It only defines the procedures and the associated YANG data model.

5.1. Procedure

The Controller creates new POT-profiles at a constant rate and communicates the POT-profile to the nodes. The controller labels a POT-profile "even" or "odd" and the Controller cycles between "even" and "odd" labeled profiles. The rate at which the POT-profiles are communicated to the nodes is configurable and is more frequent than the speed at which a POT-profile is "used up" (see table above). Once the POT-profile has been successfully communicated to all nodes (e.g., all Netconf transactions completed, in case Netconf is used as a protocol), the controller sends an "enable POT-profile" request to the ingress node.

All nodes maintain two POT-profiles (an even and an odd POT-profile): One POT-profile is currently active and in use; one profile is standby and about to get used. A flag in the packet is indicating whether the odd or even POT-profile is to be used by a node. This is to ensure that during profile change the service is not disrupted. If the "odd" profile is active, the Controller can communicate the "even" profile to all nodes. Only if all the nodes have received the POT-profile, the Controller will tell the ingress node to switch to the "even" profile. Given that the indicator travels within the packet, all nodes will switch to the "even" profile. The "even" profile gets active on all nodes and nodes are ready to receive a new "odd" profile.

Unless the ingress node receives a request to switch profiles, it'll continue to use the active profile. If a profile is "used up" the ingress node will recycle the active profile and start over (this could give rise to replay attacks in theory - but with 2^32 or 2^64 packets this isn't really likely in reality).

5.2. YANG Model

This section defines that YANG data model for the information exchange between the Controller and the nodes.

```
   module ietf-pot-profile {

     yang-version 1;

     namespace "urn:ietf:params:xml:ns:yang:ietf-pot-profile";

     prefix ietf-pot-profile;

     organization "IETF xxx Working Group";

     contact "";

     description "This module contains a collection of YANG
                  definitions for proof of transit configuration
                  parameters. The model is meant for proof of
                  transit and is targeted for communicating the
                  POT-profile between a controller and nodes
                  participating in proof of transit.";

     revision 2016-06-15 {
       description
         "Initial revision.";
       reference
         "";
     }

     typedef profile-index-range {
       type int32 {
         range "0 .. 1";
       }
       description
         "Range used for the profile index. Currently restricted to
          0 or 1 to identify the odd or even profiles.";
     }


     grouping pot-profile {
       description "A grouping for proof of transit profiles.";
       list pot-profile-list {
         key "pot-profile-index";
         ordered-by user;
         description "A set of pot profiles.";

         leaf pot-profile-index {
           type profile-index-range;
           mandatory true;
           description
             "Proof of transit profile index.";
```

```
        }

        leaf prime-number {
          type uint64;
          mandatory true;
          description
            "Prime number used for module math computation";
        }

        leaf secret-share {
          type uint64;
          mandatory true;
          description
            "Share of the secret of polynomial 1 used in computation";
        }

        leaf public-polynomial {
          type uint64;
          mandatory true;
          description
            "Pre evaluated Public polynomial";
        }

        leaf lpc {
          type uint64;
          mandatory true;
          description
            "Lagrange Polynomial Coefficient";
        }

        leaf validator {
          type boolean;
          default "false";
          description
            "True if the node is a verifier node";
        }

        leaf validator-key {
          type uint64;
          description
            "Secret key for validating the path, constant of poly 1";
        }

        leaf bitmask {
          type uint64;
          default 4294967295;
          description
            "Number of bits as mask used in controlling the size of the
```

```
            random value generation. 32-bits of mask is default.";
        }
      }
    }

    container pot-profiles {
      description "A group of proof of transit profiles.";

      list pot-profile-set {
        key "pot-profile-name";
        ordered-by user;
        description
          "Set of proof of transit profiles that group parameters
           required to classify and compute proof of transit
           metadata at a node";

        leaf pot-profile-name {
          type string;
          mandatory true;
          description
            "Unique identifier for each proof of transit profile";
        }

        leaf active-profile-index {
          type profile-index-range;
          description
            "Proof of transit profile index that is currently active.
             Will be set in the first hop of the path or chain.
             Other nodes will not use this field.";
        }

        uses pot-profile;
      }
    /*** Container: end ***/
    }
  /*** module: end ***/
  }
```

6. IANA Considerations

IANA considerations will be added in a future version of this document.

7. Manageability Considerations

Manageability considerations will be addressed in a later version of this document.

8. Security Considerations

Different security requirements achieved by the solution approach are discussed here.

8.1. Proof of Transit

Proof of correctness and security of the solution approach is per Shamir's Secret Sharing Scheme [SSS]. Cryptographically speaking it achieves information-theoretic security i.e., it cannot be broken by an attacker even with unlimited computing power. As long as the below conditions are met it is impossible for an attacker to bypass one or multiple nodes without getting caught.

- If there are k+1 nodes in the path, the polynomials (POLY-1, POLY-2) should be of degree k. Also k+1 points of POLY-1 are chosen and assigned to each node respectively. The verifier can re-construct the k degree polynomial (POLY-3) only when all the points are correctly retrieved.

- The Shares of the SECRET (i.e., points on POLY-1) are kept secret by individual nodes.

An attacker bypassing a few nodes will miss adding a respective point on POLY-1 to corresponding point on POLY-2 , thus the verifier cannot construct POLY-3 for cross verification.

8.2. Anti Replay

A passive attacker observing CML values across nodes (i.e., as the packets entering and leaving), cannot perform differential analysis to construct the points on POLY-1 as the operations are done modulo prime. The solution approach is flexible, one could use different points on POLY-1 or different polynomials as POLY-1 across different paths, traffic profiles or service chains.

Doing differential analysis across packets could be mitigated with POLY-2 being be random. Further an attacker could reuse a set of RND and all the intermediate CML values to bypass certain nodes in later packets. Such attacks could be avoided by carefully choosing POLY-2 as a timestamp concatenated with a random string. The verifier could use the timestamp to mitigate reuse within a time window.

8.3. Anti Tampering

An active attacker could not insert any arbitrary value for CML. This would subsequently fail the reconstruction of the POLY-3. Also an attacker could not update the CML with a previously observed

value. This could subsequently be detected by using timestamps within the RND value as discussed above.

8.4. Recycling

The solution approach is flexible for recycling long term secrets like POLY-1. All the nodes could be periodically updated with shares of new SECRET as best practice. The table above could be consulted for refresh cycles (see Section 4).

8.5. Redundant Nodes and Failover

A "node" or "service" in terms of POT can be implemented by one or multiple physical entities. In case of multiple physical entities (e.g., for load-balancing, or business continuity situations - consider for example a set of firewalls), all physical entities which are implementing the same POT node are given that same share of the secret. This makes multiple physical entities represent the same POT node from an algorithm perspective.

8.6. Controller Operation

The Controller needs to be secured given that it creates and holds the secrets, as need to be the nodes. The communication between Controller and the nodes also needs to be secured. As secure communication protocol such as for example Netconf over SSH should be chosen for Controller to node communication.

The Controller only interacts with the nodes during the initial configuration and thereafter at regular intervals at which the operator chooses to switch to a new set of secrets. In case 64 bits are used for the data-records "CML" and "RND" which are carried within the data packet, the regular intervals are expected to be quite long (e.g., at 100 Gbps, a profile would only be used up after 3100 years) - see Section 4 above, thus even a "headless" operation without a Controller can be considered feasible. In such a case, the Controller would only be used for the initial configuration of the POT-profiles.

8.7. Verification Scope

The POT solution defined in this document verifies that a data-packet traversed or transited a specific set of nodes. From an algorithm perspective, a "node" is an abstract entity. It could be represented by one or multiple physical or virtual network devices, or is could be a component within a networking device or system. The latter would be the case if a forwarding path within a device would need to be securely verified.

8.7.1. Node Ordering

POT using Shamir's secret sharing scheme as discussed in this document provides for a means to verify that a set of nodes has been visited by a data packet. It does not verify the order in which the data packet visited the nodes. In case the order in which a data packet traversed a particular set of nodes needs to be verified as well, alternate schemes that e.g., rely on nested encryption could to be considered.

8.7.2. Stealth Nodes

The POT approach discussed in this document is to prove that a data packet traversed a specific set of "nodes". This set could be all nodes within a path, but could also be a subset of nodes in a path. Consequently, the POT approach isn't suited to detect whether "stealth" nodes which do not participate in proof-of-transit have been inserted into a path.

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10. References

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