Enabling Efficient Source and Path Verification via Probabilistic Packet Marking

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***Abstract*—The Internet lacks verification of source authenticity and path compliance between the planned packet delivery paths and the real delivery paths, which allows attackers to construct attacks like source spoofing and traffic hijacking attacks. Thus, it is essential to enable source and path verification in networks to detect forwarding anomalies and ensure correct packet delivery. However, most of the existing security mechanisms can only capture anomalies but are unable to locate the detected anomalies. Besides, they incur significant computation and communication overhead, which exacerbates the packet delivery performance. In this paper, we propose a high-efficient packet forwarding verification mechanism called PPV for networks, which verifies packet source and their forwarding paths in real time. PPV enables probabilistic packet marking in routers instead of verifying all packets. Thus, it can efficiently identify forwarding anomalies by verifying markings. Moreover, it localizes packet forwarding anomalies, e.g., malicious routers, by reconstructing packet forwarding paths based on the packet markings. We implement PPV prototype in Click routers and commodity servers, and conducts real experiments in a real testbed built upon the prototype. The experimental results demonstrate the efficiency and performance of PPV. In particular, PPV significantly improves the throughput and the goodput of forwarding verification, and achieves around 2 times and 3 times improvement compared with the-state-of-art OPT scheme, respectively.**

***Index Terms*—Source and Path Verification, Fault Localization**

I. INTRODUCTION

The current Internet is vulnerable to various types of malicious attacks, such as source spoofing and flow hijacking because it lacks source authentication and path validation [1] [2] [3]. All network entities (e.g., packet source, intermediate router, and destination) assume that the incoming packets are authentic although they may be counterfeited or modified [4] [5] [6]. Additionally, the connectionless nature of IP packet delivery cannot ensure path compliance between actual forwarding paths in the data-plane and the computed paths in the control-plane [7]. Therefore, source authentication and path validation are essential in IP network to detect packet forwarding anomalies and ensure correct packet delivery. Here, source authentication verifies whether a received packet indeed originates from the real sender claimed by the source address of IP packet, and path validation confirms whether the actual forwarding path taken by traffic [8] is consistent with the paths selected by the source, or computed according to the routing policies of an ISP, enterprise, or datacenter network.

Efficiency is critical for the practical deployment of Internet security protocols [9]. Unfortunately, existing schemes for source and path verification impose a non-trivial overhead since they require *all* intermediate entities to perform cryptographic operations upon receiving packets. These operations (*e.g.*, sign and verification) bring a significant verification overhead. For example, prior AS-level packet verification mechanisms [1] [10] [11] verify every forwarded packet hop-by-hop during its transmission. Such hop-by-hop processing could significantly reduce the forwarding efficiency (e.g., throughput and goodput) of the network. As packets can also be hijacked due to attacks on systems such as the OSPF protocol [12] [13], several router-level source and path verification approaches [2] [3] [14] [15] have been proposed. However, they all require the source to initialize markings in packet headers for all intermediate entities, which imposes higher communication overhead. Meanwhile, each intermediate entity is required to verify these markings once receiving a packet, adding additional verification overhead and potentially reducing the quality of service in networks. Besides the high overhead, prior approaches can only capture forwarding anomalies but are unable to localize these anomalies. In particular, the intermediate entities will directly drop the packets once any anomaly is detected, while no feedback is sent to end-hosts. Without such verification feedback from entities, the end-hosts cannot localize a fault during packet transmission, which is not conducive to network repair and management.

In this paper, we propose PPV, a highly efficient mechanism for verifying source authenticity and path compliance. In PPV, entities perform probabilistic packet marking for each packet and generate a key-hashed Message Authentication Code (MAC) for that packet. We show that by using PPV each packet only requires to be marked by at most two entities (rather than all entities), thereby greatly reducing the computation overhead of intermediate entities and the verification overhead of the destination. Through the evaluation on our prototype, PPV introduces a modest 6.25% mean communi-

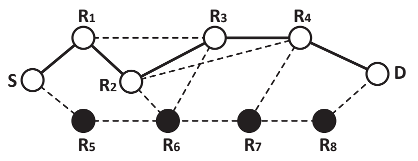


Fig. 1. The example of path inconsistency attacks with intended forwarding path $\Psi = \langle R_1, R_2, R_3, R_4 \rangle$ and a series of undesired actual paths Φ.

cation overhead[1] (64 bytes). In particular, compared with the state-of-the-art scheme, OPT [2], it reduces the communication overhead by 75%. Additionally, without requiring special hardware, PPV has better forwarding efficiency than OPT since during a packet transmission, PPV performs much smaller numbers of MAC computations than OPT. As a result, PPV achieves around twice the forwarding throughput and three times the forwarding goodput of OPT. Further, PPV allows the destination to efficiently localize faulty entities that counterfeit source information or hijack packets by recomputing the received markings in the packets and reconstructing packet forwarding paths. Compared with prior IP traceback schemes [16] [17] [18], the convergence delay of PPV for constructing actual forwarding paths is bounded. PPV enables entities to probabilistically make their marking on packets according to our defined probability. In practice, our experimental results show that PPV can efficiently localize the fault within 0.80 ms in our click router implementation.

The contributions of the paper are three-fold:

- We propose PPV, a new probabilistic packet verification scheme for verifying source authenticity and path compliance, which imposes less overhead than prior solutions.
- In addition to source and path verification, PPV also has a fault localization function that localizes the fault within 0.80 ms for different packet sizes under the average router-level path length of the Internet.
- We implement the PPV prototype on Click routers and commodity servers, and perform extensive evaluations to demonstrate the technical feasibility of PPV.

The remainder of this paper is organized as follows: In Section II, we present the adversary model. In Section III, a high-level overview of PPV scheme is provided. In Section IV, we introduce the design details of PPV. We perform some security analysis of the attack model in Section V. In Section VI, the experimental performance and evaluation is presented.We cover the related previous work in the field of source authentication and path validation in Section VII. Finally, we conclude in Section VIII.

II. ADVERSARY MODEL

In this paper, we assume an adversary can compromise a sender or an intermediate router on the delivery path so that it can spoof a source addresses or change forwarding paths.

A. Source Spoofing and Path Inconsistency

In a network, a packet source can be spoofed and forwarding paths can also be changed (e.g., packet hijacking) due to the misbehavior from compromised entities. The adversary can launch a source spoofing attack by compromising either a packet sender or a malicious router to counterfeit or tamper with the source address in the packet header. Compromised routers can also change packet forwarding paths by violating forwarding policies, which makes actual forwarding path (denoted by Φ) differ from intended forwarding path (denoted by Ψ). With $\Psi = \langle R_1, R_2, R_3, R_4 \rangle$ in Fig. 1, we summarize various types of path inconsistency as following descriptions.

Routing addition. The packets are abnormally forwarded to other entities out of Ψ and then delivered to Ψ, such as the additional R_6 between R_2 and R_3 in Fig. 1.

Routing skipping. The packets skip one or more entities and are instead forwarded to other downstream entities on Ψ, such as the delivery from R_1 to R_3 (ignoring R_2) in Fig. 1.

Unordered routing path. The packets are delivered through the entities that are same but out-of-order compared with entities on Ψ, such as $\Phi = \langle R_1, R_3, R_2, R_4 \rangle$ in Fig. 1.

Routing detour. The packets are maliciously forwarded away from Ψ and then deliberately back to Ψ after a short travel, e.g., the delivery from R_2 to R_6, R_7, and then to R_4 in Fig. 1.

Path complete deviation. The packets are delivered through entities that are totally different from the entities on Ψ, such as $\Phi = \langle R_5, R_6, R_7, R_8 \rangle$ in Fig. 1.

B. Sophisticated Attacks

In addition to the above, there are more advanced attacks that should be taken into consideration when guaranteeing network security with regard to verifying the source and path.

Combined attack. An adversary can control multiple compromised entities for launching combined attacks, which may consist of several types of the basic attacks described above.

Routing collusion. The compromised entities can collude with each other to destroy the veracity of the source and the path so that they can launch any of the basic attacks together.

Fault location hidden. An adversary can make the unreliable sender or malicious router(s) try to hide their location to obviate the source and path verification.

III. PPV DESIGN OVERVIEW

In this section, we will present a high-level description of the proposed PPV that performs source and path verification.

A. Scope and Assumptions

This paper aims to verify packet source and forwarding path of end-to-end communication in the data plane. We assume that the existing secure routing protocols can enable end-hosts to learn the intended forwarding path Ψ at AS- or router-level granularity. For example, the AS-level path can be obtained through some BGP related protocols [1] [19]; whereas, SCION [20] or Pathlet routing [21] can make the source specify the router-level forwarding path in the packet header. The end-hosts can also obtain the necessary symmetric keys, shared with intermediate entities of the intended path, using the existing DRKey protocols [2]. DRKey uses stateless operation in entities and does not require each entity to store the symmetric keys, avoiding DoS attack by state exhaustion.

Our proposed scheme, PPV, works at a flow-level granularity so as to achieve source authentication and path validation. It is unnecessary to perform strong per-packet forwarding

[1]Communication overhead is defined as the length of extra bytes in the packet header used for source and path verification.

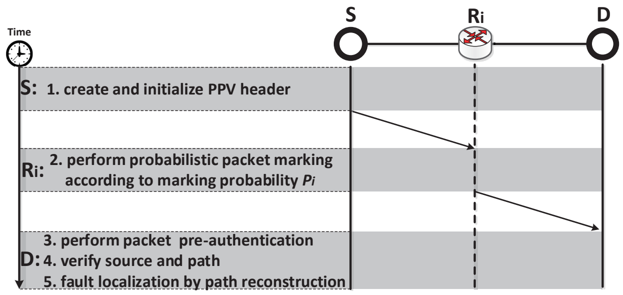

Time
S
Ri
D
S: 1. create and initialize PPV header
Ri: 2. perform probabilistic packet marking according to marking probability Pi
3. perform packet pre-authentication
D: 4. verify source and path
5. fault localization by path reconstruction

Fig. 2. The PPV overview when the packet is delivered through R_i towards D. Different entities handle the packets according to the responding rules.

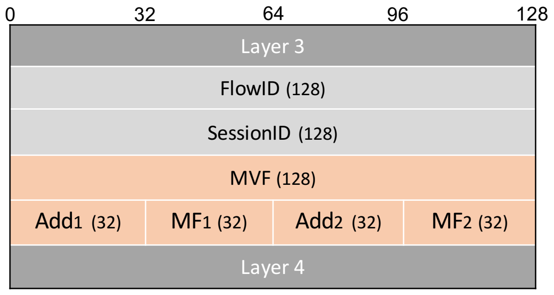


Fig. 3. The format of PPV header between Layer 3 and Layer 4 that contains seven fields and takes a fixed length of 64 bytes.

verification to achieve perfect detection as source spoofing and path inconsistency of one single packet cannot, usually, pose a serious threat to the connection [22]. Instead, flow-level forwarding verification can greatly reduce the overhead compared with the per-packet verification schemes.

B. Design Challenges

We highlight the design challenges of source and path verification by introducing an intuitive but insecure strawman approach that is built upon an IP traceback scheme. Let us consider the source S communicates with the destination D. Before each packet departs, S reserves several fields in packet header. During packet delivery, entities will sign its address on theses fields in order. D will perform the packet verification according to this address sequence. However, an offending entity can disturb the verification of D, by such signing a counterfeit address or tampering some signed addresses. Without encryption techniques, the entities are all open to counterfeiting or modification attacks [23]. However, using encryption techniques can introduce non-negligible overhead, such as higher verification overhead for encryted markings, which impacts the forwarding efficiency. Thus, there is a tradeoff between higher security and lower overhead. i) Simply using the entity address as a marking occupies few bytes and brings a lower overhead, but it is open to marking modification and counterfeiting attacks. ii) Using cryptographic techniques can strengthen security but with increased overhead, lowering the forwarding efficiency, such as throughput and goodput.

C. PPV Overview

PPV provides probabilistic packet marking for each entity, bridging the gap between security and performance. PPV enables each packet to record the markings of a subset of the entities instead of all entities on forwarding path, introducing a lower communication overhead. This also reduces the overall packet verification overhead as every packet is not marked by all entities. PPV eschews the use of a simple address as a marking, but instead improves security by employing a cryptographic marking based on a MAC using symmetric keys.

In the network, the forwarding path *Path*, including Ψ and Φ, can be considered as the composition of many links L_i between two entities as Eq. 1 shows. Each link L_i is determined by two neighbor entities, such as L_0 for S and R_1, L_i for R_i and R_{i+1}, and L_n for R_n and D.

$$Path = \langle L_0, L_1, \ldots, L_i, \ldots, L_n \rangle . \tag{1}$$

PPV aims to make each packet collect one connection L_i instead of all connections during its travel from S to D. Thus, only two fields should be reserved in a packet by S, which minimizes communication overhead. The two reserved fields are designed to store two markings of neighbored entities. The high-level PPV operations are sketched in Fig. 2.

PPV header initialization. Before packet's departure, S first creates a new PPV header between Layer 3 (IP header) and Layer 4 (TCP header) as Fig. 3 shows. The seven fields in PPV header are then all initialized for later marking and verification.

Probabilistic packet marking. On receiving a packet, two neighbored entities probabilistically make encrypted markings on PPV header. In PPV, the marking probability of each entity is well designed for reduced convergence delay when the destination performs packet verification.

Packet pre-authentication. The packet pre-authentication is mainly used to verify the integrity of packet data and the validity of markings, which protects the packet data or markings in PPV header from modification or counterfeit.

Source and path verification. In PPV, each packet records two markings of neighbor entities, and the destination can check these markings. If fails, it illustrates the source or the forwarding path has been modified by some malicious entity.

Path reconstruction and fault localization. If the verification fails, D will reconstruct Φ to localize the fault, using the collected connections L_i, which are all obtained from a series of the received PPV headers. The comparison between Φ and Ψ will contribute to localizing the offending entity.

IV. THE DESIGN DETAILS OF PPV

In this section, we detail our proposed PPV to implement end-to-end forwarding verification. For the packet delivery, the sender first initializes PPV header (Section IV-A), intermediate entities perform probabilistic packet marking (Section IV-B), and the destination carries out packet pre-authentication (Section IV-C), source and path verification (Section IV-D), and fault localization (Section IV-E).

A. PPV header initialization

PPV header is used to store markings made by intermediate entities during packet transmission, which is employed for packet forwarding verification. For an outgoing packet, the PPV header is created between Layer 3 and Layer 4, as shown in Fig. 3. It contains seven fields: FlowID, PacketID, Marking Verification Field (MVF), two address fields (Add_1 and Add_2) and two marking fields (MF_1 and MF_2).

FlowID is an identifier of network traffic, calculated with hash over six elements: addresses of end-hosts (*src* and *dst*), ports of end-hosts (*srcp* and *dstp*), protocol (*prtl*), and the hash value of K_{SD} shared between S and D, as shown in Eq. 2. FlowID can also mitigate source spoofing as the packet sender does not have the valid K_{SD}.

$$FlowID = H(src||srcp||dst||dstp||prtl||H(K_{SD})). \tag{2}$$

PacketID is a packet identifier, which is the MAC value of FlowID and packet payload keyed with K_{SD}, see Eq. 3. PacketID can be used to perform data authentication and prevent replay attacks.

$$PacketID = MAC_{K_{SD}}(FlowID||payload). \tag{3}$$

The field MVF is used to prevent the markings in MF_1 and MF_2 from being modified and counterfeited during packet transmission. S initializes MVF as the value mvf_0 (see Eq. 4). Note that mvf_0 varies with different packets and can be calculated only by S and D using K_{SD}.

$$mvf_0 = MAC_{K_{SD}}(PacketID). \tag{4}$$

The fields Add_1 and Add_2 record the addresses of two neighboring entities that insert their own markings in MF_1 and MF_2, respectively. Two marking fields have two states: empty (filled with all zeros), or full (otherwise). Initially, they are all empty, representing no entity marks in PPV header.

B. Probabilistic Packet Marking of Routers

As stated earlier, the intermediate entities perform probabilistic packet marking to reduce encryption overhead. We respectively define P, C and N as the address of previous, current and next entity during packet transmission. On receiving a packet, R_i will first check the status of MF_1 and MF_2. If they are all empty, R_i will mark its marking M_i on MF_1 according to its marking probability P_i (described shortly). The marking M_i is the MAC operation value of *src* and TTL (time-to-live), P and PacketID keyed with K_i, as Eq. 5 shows. The source address *src* is an essential input of MAC operation, by including it, if a malicious entity launches source spoofing, this will cause an error in the marking of downstream entity and a failure of source authentication allowing detection.

$$M_i = MAC_{K_i}(src||TTL||\mathtt{P}||PacketID). \tag{5}$$

Meanwhile, Add_1 and Add_2 are respectively written as C (i.e., R_i) and N (i.e., R_{i+1}). R_i performs the MAC operation to update MVF from mvf_0 to mvf_1 as follows.

$$mvf_1 = MAC_{K_i}(mvf_0||\mathtt{C}||M_i||\mathtt{N}). \tag{6}$$

On receiving the packet, R_{i+1} finds MF_1 is full and the addresses on the fields Add_1 and Add_2 are respectively equal to the addresses of R_i and R_{i+1}. Then, R_{i+1} inserts its marking M_{i+1} into MF_2 and updates MVF to mvf_2 as shown in Eq. 7.

$$mvf_2 = MAC_{K_{i+1}}(mvf_1||M_{i+1}). \tag{7}$$

By using DRKey protocol [2], each entity dynamically recreates the symmetric key on the fly and does not store it for each flow or source, which protects entities from different types of state exhaustion DoS attacks. In PPV, the intermediate entity will drop the packet if it finds the PPV header contains the full Add_2, but not filled with its own address when MF_2 is empty. Fig. 4 shows one example of the process of probabilistic packet marking when a packet is forwarded from S to D. In this example, only R_2 and R_3 make markings in PPV header according to their marking probabilities.

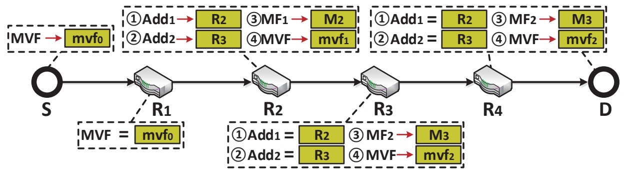


Fig. 4. An example of changing process of PPV header, where the red arrow denotes the dynamically update operation during packet delivery.

Marking probability. To verify the packet forwarding on Ψ, PPV enables D to quickly obtain all markings by setting the marking probability P_i for each entity R_i. We define Q_i as the probability that R_i's marking appears on MF_1, which is calculated by Eq. 8.

$$Q_i = (1 - P_1)(1 - P_2)...(1 - P_{i-1})P_i. \tag{8}$$

UPPM [24] has proved equal appearing probability, i.e., $Q_1 = Q_2 = ... = Q_n$ can bring the minimum convergence time. In PPV, we set P_i using the TTL value as: $P_i = TTL^{-1}$. PPV can set the value of P_i by adjusting the TTL value a in packet header when the packets depart from S. Next, we will provide the proof for $Q_1 = Q_2 = ... = Q_n$ under the setting of P_i. We denote χ ($\chi \geq n$) as the initial TTL value when the packets depart from S. Based on Eq. 8, Q_n can be calculated as follows, demonstrating Q_i is a constant value.

$$Q_i = \frac{\chi - 1}{\chi} \cdot \frac{\chi - 2}{\chi - 1} \cdot ... \cdot \frac{\chi - (i-1)}{\chi - (i-2)} \cdot \frac{1}{\chi - (i-1)} = \frac{1}{\chi} \tag{9}$$

Thus, all marks have the same probability of appearing at D using P_i, i.e., $Q_1 = Q_2 = ... = Q_n$.

We denote P_0 as the value of Eq. 9. Thus, P_0 can be presented by Eq. 10. On receiving a packet, each entity can calculate its own marking probability P_i regardless of the number of flows and path lengths. Note that computing P_i causes a smaller marking probability of entities close to S, to bring an equal Q_i of all marks, overcoming the otherwise bias of hops at the beginning of the path which equal probability marking schemes suffer from.

$$P_0 = \frac{1}{\chi} \quad , \quad 0 \leq P_0 \leq \frac{1}{n}. \tag{10}$$

The probability that R_{i+1} marks on MF_2 only depends on whether a previous entity R_i has inserted R_{i+1}'s address into Add_2, rather than the probability P_{i+1}. As for P_0, we define *standard probability* (*SP*) when $P_0 = 1/n$, in which two markings of at least one pair of entities will be certainly recorded in PPV header, because P_i tends to 1 when packets are close to D. More especially, $P_n = 1$ illustrates R_n certainly marks on MF_1 if none of upstream entities have marked in PPV header. Note that the marking probability P_i depends on the current TTL value. In this case, an offending entity, say R_α, can launch a **TTL attack** to confuse TTL value, and make the marking probabilities of downstream entities abnormal. For example, R_α can either make TTL value larger to bring a smaller $P_{\alpha+1}$, or decrease TTL value greatly to make $R_{\alpha+1}$

Algorithm 1 Source and path verification pseudo code.

```
1: function SOURCE AND PATH VERIFICATION( )
2: Require:
3:     $R_i$, $R_j$, $M_i$, $M_j$, $K_i$, $K_j$, $\Psi$, $FlowID$
4: Compute:
5:     $M_i' = MAC_{K_i}(src||TTL||R_{i-1}||FlowID)$
6:     $M_j' = MAC_{K_j}(src||TTL||R_{j-1}||FlowID)$
7:     if ($M_i' == M_i$ && $M_j' == M_j$) then
8:         Probabilistic verification for source and path succeeds.
9:     else
10:        Probabilistic verification for source and path fails.
11:    end if
12: end function
```

mark certainly. PPV can avoid this TTL attack by using the value of TTL to calculate R_i's marking M_i as Eq. 5 shows. If the TTL value on IP header is maliciously modified, the downstream entities will generate erroneous markings, causing the failure of later verification.

C. Packet Pre-authentication

The packet pre-authentication includes data authentication, which verifies the integrity of packet data, and the marking validation, ensuring that the received PPV header is reliable.

Packet data authentication. On receiving each packet, D first performs data authentication, because if the packet data is modified, it is meaningless to verify the source address and forwarding path. The field PacketID is employed to achieve this requirement. Specifically, D first recomputes the value of PacketID using Eq. 3 and then compares it with the received PacketID in PPV header. With passing the data authentication, the following marking verification can be carried out.

Marking validity authentication. The markings on MF_1 and MF_2 are used by PPV for source and path verification. With symmetric keys, D recomputes mvf_2, the value of MVF, to verify whether the markings on the two marking fields have been modified. The equivalence between the recalculated mvf'_2 and the received mvf_2 in the PPV header illustrates the markings on two marking fields are valid and have not been modified. D will employ the valid markings for later verification and fault localization.

D. Source Authentication and Path Validation

Source and path verification aims to capture anomalies during packet transmission. After packet pre-authentication, D then carries out source and path verification. Due to the probabilistic packet marking process, MF_1 and MF_2 may be empty when the packet arrives at D, with the probability P_e:

$$P_e = \prod_{i=1}^{n}(1 - P_i) = 1 - n \cdot P_0 \quad , \quad 0 \le P_0 \le \frac{1}{n}. \tag{11}$$

If this is the case, D will ignore this verification of source and path, and verify the next marked packet. From Eq. 11, we know if P_0 takes the value of SP, *i.e.*, $P_0 = 1/n$, D will never receive an empty marking field in PPV header.

Algorithm 1 shows the process of source authentication and path validation. According to the addresses R_i and R_j on the fields Add_1 and Add_2, D will use the respective symmetric keys K_i and K_j to recalculate the markings: M_i' and M_j'. Then the comparison between recalculated M_i' (M_j') and received M_i (M_j) in PPV header will determine whether source and path verification succeeds. If unequal, it illustrates that the source address and/or the forwarding path have been modified.

Confidence degree. For source and path validation, it is unnecessary to perform strong per-packet verification, as a single packet is unlikely to pose a threat to D. In this paper, PPV works on flow granularity, in which the marked packet can be used to verify the path integrity of two adjacent entities. In this case, one successful verified packet cannot represent the reliability of the entire forwarding path. We employ a parameter called confidence degree $\mathcal{C}$ to show the credibility of the whole forwarding path where $\mathcal{C}$ is the proportion between the reliable entities and all forwarding entities on the path after validating a certain number of packets. If the forwarding path contains n entities, there are n connections ignoring the first connection (*i.e.*, L_0) between S and R_1. The connection L_i is uniquely determined by R_i and R_{i+1}, which can be found on Add_1 and Add_2. Thus, the confidence degree $\mathcal{C}$ can be evaluated by the proportion of legal verified connections. We use X_i as a decision variable, denoting whether connection L_i is verified, that is to say whether M_i and M_{i+1} have all passed the validation after m packets' arriving. Thus, X_i is:

$$X_i = \begin{cases} 1 & L_i \text{ is verified after receiving } m \text{ packets} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

We define X as the sum of X_i, *i.e.*, $X = \sum_{i=1}^{n} X_i$. Using the known marking probability, we know that the expectation of the number of marked packets is mnP_0 after receiving m packets. Among these marked packets, every connection L_i has the equal probability $1/n$ to appear on PPV header (see Section IV-B). So the probability that L_i does (not) appear on PPV header, i.e., is (not) validated by D is:

$$P\{X_i\} = \begin{cases} (1 - 1/n)^{mnP_0} & X_i = 0 \\ 1 - (1 - 1/n)^{mnP_0} & X_i = 1 \end{cases} \tag{13}$$

So the expected number of all verified links is as follows.

$$E(X) = E\left(\sum_{i=1}^{n} X_i\right) = n[1 - (1/n)^{mnP_0}]. \tag{14}$$

Then, the confidence degree $\mathcal{C}$ is:

$$\mathcal{C} = \frac{E(X)}{n} = 1 - (1 - \frac{1}{n})^{mnP_0}. \tag{15}$$

Fig. 5 illustrates the relationship between the confidence degree $\mathcal{C}$ and the number of verified packets m at D when the path length is 5 hops and 13 hops, the average path length in AS [25] and router level [26], respectively. P_0 takes the basic probabilities of $SP_{n=5}$ = 1/5 and $SP_{n=13}$ = 1/13, and a smaller value of 0.05 that is derived from the basic probability of an assumed longest path length *i.e.,* n = 20 hops [26]. From this figure, we learn the confidence degree $\mathcal{C}$ increases with the number of packets that are verified. For example, for $SP_{n=5}$, the confidence degree of 90%, 95%, 99% and 99.9% only require around 10, 13, 21, 31 verified packets. For the same path length, the larger P_0 (*e.g.,* P_0 = 0.20) value requires fewer verified packets to reach the same $\mathcal{C}$ than the smaller value (*e.g.,* P_0 = 0.05). For the longer forwarding path, a greater number of received packets are needed to be verified to gain the same $\mathcal{C}$. For example, $\mathcal{C}$ = 99% needs 21 verified packets

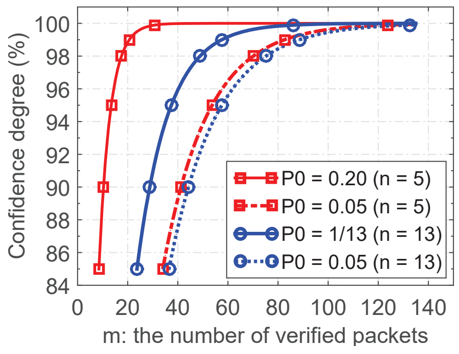


Fig. 5. The relationship between confidence degree $\mathcal{C}$ and the number of verified packets m with the average path length of AS or router level at D.

for $P_0 = SP_{n=5}$ and 58 verified packets for $P_0 = SP_{n=13}$. For the same P_0 (*e.g.*, $P_0 = 0.05$), a smaller path length can easily help to obtain a high $\mathcal{C}$ when the same number of packets are verified. In this paper, we pay more attention to analyzing the case of $P_0 = SP$ for a higher confidence degree in PPV.

E. Fault Localization

PPV uses forwarding path reconstruction to perform fault localization. In order to localize the fault, D will reconstruct Φ after the failure of source and path verification. From Add_1 and Add_2 on each marked PPV header, D can obtain a link L_i, which indicates the neighboring link relation between R_i and R_j. With a greater number of marked packets arriving, D can obtain a more identified links and thus reconstruct Φ using the existing weighted union/find algorithm [27]. After receiving a number of packets, waiting typically for convergence time T_c, the reconstructed Φ will converge to the final value, which is represented by a address sequence. The comparison between Φ and Ψ as well as between the recalculated marking M_i' and the received marking M_i contributes to localizing the faulty entities. Algorithm 2 describes the details of fault localization.

In our proposed PPV, the scope of the fault can be narrowed down to one or two entities. PPV tries to localize the first offending entity on Ψ, because its misbehavior can lead to the confusion at downstream entities. In other words, it is meaningless to locate all its downstream entities as their apparent misbehavior actually results from the first fault.

Convergence delay. In this paper, we define convergence delay T_c as the expected number of received packets used to reconstruct the forwarding path. While T_c is not strictly a time unit, it is proportional to time for a given data rate. We define a *useful link* as a link not appearing in the previous packets of the flow. Due to $Q_i = P_0$, as described in Section IV-D, the probability of getting a useful connection is $n{\cdot}P_0$ and $(n\text{-}1){\cdot}P_0$ respectively from the first and second received packet, and $(n\text{-}j\text{+}1){\cdot}P_0$ from the j-th received more generally. Using a similar analysis from other research [16] [24], the derivation of T_c is a form of the coupon collector problem and is equal to:

$$\begin{aligned} T_c &= \frac{1}{n \cdot P_0} + \ldots + \frac{1}{(n-j+1)\cdot P_0} + \ldots + \frac{1}{P_0} \\ &= \frac{1}{P_0}\sum_{i=1}^{n}\frac{1}{k} \approx \frac{\ln n + \mathcal{W}}{P_0} \quad , \quad \mathcal{W} \approx 0.577. \end{aligned} \tag{16}$$

Algorithm 2 Fault localization pseudo code.

```
1: function FAULT LOCALIZATION( )
2: Require:
3:     $\Phi = \langle R_1, R_2, \ldots, R_m \rangle$,  $M_1, M_2, \ldots, M_m$
4:     $\Psi = \langle R_1', R_2', \ldots, R_n' \rangle$,  $M_1', M_2', \ldots, M_n'$
5:     $src$, $srcp$, $dst$, $dstp$, $prtcl$, $K_{SD}$, $FlowID$
6: Compute:
7:     $FlowID' = H(src||srcp||dst||dstp||prtcl||K_{SD})$
8:     if ($FlowID' == FlowID$) then
9:         Source host is credible.
10:    else
11:        Source host is localized for its address spoofing.
12:    end if
13:    $l = max\{n, m\}$
14:    for $0 < t \le l$ do
15:        if ($R_t == R_t'$) then
16:            if ($M_t == M_t'$) then
17:                Verification succeeds up to $R_t$
18:            else
19:                $R_{t-1}$ and $R_t$ can be localized.
20:            end if
21:        else
22:            $R_{t-1}$ can have changed forwarding path.
23:        end if
24:    end for
25: end function
```

V. SECURITY ANALYSIS

We argue that PPV provides the verification for both the origin and the forwarding path, and discuss why PPV is resilient to the adversary models described in Section II.

A. Defense Against Source Address Spoofing

Without the symmetric key K_{SD}, a malicious sender cannot calculate the valid PacketID, causing an error during packet pre-authentication. Although a malicious sender can use PacketID in other benign packets that have been sent by a reliable sender, D can also prevent this due to detecting a replay attack through a suitable replay detection cache. Additionally, with a spoofed source, packets carrying two markings will not pass the verification as the spoofed origin will be employed and result in a series of erroneous markings. When an entity launches a spoofing attack by counterfeiting or tampering source address, the packets will be dropped at D due to the incorrect results of packet pre-authentication.

B. Defense Against Routing Path Inconsistency

PPV is sensitive to path inconsistency due to using both the TTL value and the address of a 1-hop upstream entity to compute a valid marking. If there is an entity changing the forwarding path by the means described in Section II-A, the markings of downstream entities will be incorrect, due to the false TTL value and the illegal previous hop address.

For routing addition and routing detour, the packets are forwarded to another entity not included in Ψ by an offending entity (say R_τ), and then delivered to the entity (say R_φ, $\varphi > \tau$) on Ψ. Consequently, R_φ will generate an erroneous marking M_φ calculated with an incorrect TTL value and address of the previous entity in Ψ. Additionally, the additional entities no in Ψ between R_τ and R_φ will also create and insert erroneous markings into the PPV header, which causes the packet to be dropped at D. As for routing skipping, for example, the offending entity R_τ directly forwards the packets to $R_{\tau+\varepsilon}$ (ε >1) on Ψ and skips the entities between R_τ and $R_{\tau+\varepsilon}$, in which the marking $M_{\tau+\varepsilon}$ will be incorrect because of using incorrect TTL and unintended previous address. In this case, R_τ can also maliciously insert $R_{\tau+1}$'s address into Add_2 for more interference, which brings no opportunity for $R_{\tau+\varepsilon}$ and other downstream entities to mark their markings in the PPV header for evading the verification at D. However, PPV enables $R_{\tau+\varepsilon}$ to drop the packets once finding a full Add_2 and an empty MF_2. For further malicious interference, R_τ could also counterfeit markings $M_{\tau+1}$ on MF_2 to prevent downstream entities from discarding packets, or steer an already-marked packet on an arbitrary path to D, in which D can detect the invalid markings via packet pre-authentication and then drop the packets. Similar to the analysis of route skipping, the out-of-order forwarding path can also be addressed in PPV under the basic attack or further interference. If a complete path deviation occurs, D will drop the packets due to lacking symmetric keys shared with intermediate entities.

C. Defense Against Sophisticated Attacks

For the higher security requirements, there are many sophisticated attacks we should take into consideration when verifying the origin and the forwarding path. PPV can provide strong defense against a combined attack consisting of multiple types of basic attacks. Specifically, if both source spoofing and path inconsistency occur simultaneously, the downstream entities will mark erroneously in the PPV header due to using a modified source address, inaccurate TTL and incorrect previous address as the inputs to the marking calculation. As PPV works at the flow granularity, the offending entity can launch further sophisticated attacks, only aiming at the subset of packets of this flow, which could cause multiple actual forwarding paths. In this case, D can reconstruct one or more Φ and localize the offending entity using Algorithm 2.

As for routing collusion, if there are two malicious entities, *e.g.*, R_τ and R_φ, they can collude with each other to launch sophisticated attacks. Before packets reach R_φ, R_τ can either spoof the source or change the packet forwarding path. On receiving the packet, R_φ clears the Add_1 (Add_2) and MF_1 (MF_2) to stop D from receiving the markings of entities between R_τ and R_φ for the purpose of hiding R_τ's misbehavior. In this case, the reconstructed Φ differs from Ψ, which helps to identify and localize the fault R_τ. As for attacking fault location, where a hidden adversary tries to control an unreliable sender or entity so as to hide its location for modifying the source or the forwarding path: in PPV, the downstream entities will create erroroneous markings, causing a verification failure. With the reconstructed Φ and collected markings, D can localize or narrow down the scope of the fault. To interfere with detection, the adversary could stop the downstream entity from marking the false markings in the PPV header by means of inserting a counterfeit marking. However, without access to the symmetric key, the marking or MVF value will not be correctly calculated or updated, which brings about the failure of packet pre-authentication at D. The adversary could make the packets skip over one or more entities to stop them from marking in the PPV header. However, PPV enables D to reconstruct the actual forwarding path and then localize this fault.

PPV can also provide defense against modification and counterfeit of the marking. When the adversary modifies or counterfeits the marking of another entity, the packet pre-authentication will fail, because the recomputed MVF is not equal to the received MVF. The marked packets with invalid markings will be dropped by D. A replay attack can also be addressed in PPV. When receiving a packet with the same PacketID with the previously received packet, D will consider it as a replay attack because PacketID cannot be counterfeited without the corresponding symmetric key.

VI. PERFORMANCE EVALUATION

In this section, we evaluate PPV by using the following important metrics. (i) Packet communication overhead that indicates the cost of forwarding verification. (ii) Network throughput and goodput that represent the performance of packet verification by PPV. (iii) Fault localization delay that is to evaluate the efficiency/time of fault localization.

We implemented the PPV scheme described in Section IV and compare it with the-state-of-the-art OPT scheme [2]. We use the same encryption algorithm as OPT, *i.e.*, the AES-CBC-MAC algorithm [28], to perform the MAC operation used in the (re)calculation of router marking and update for MVF, and use SHA-3 algorithm [29] to calculate the hash of strings, such as PacketID initialization. For symmetric keys, PPV employs 128-bits keys shared between routers and end-hosts. We evaluate PPV with respect to the performance metrics, described above, for source and path verification.

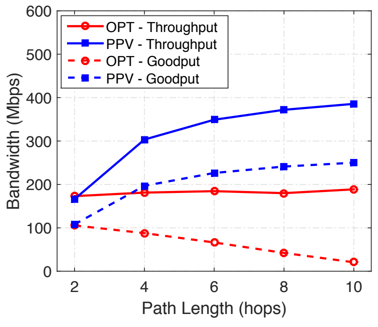
A. Communication Overhead and Ratio

The communication overhead (CO) is the extra portion of the normal IP packet (i.e., PPV header and OPT header). From Section IV-A, we know that PPV header is a fixed-length of 64 bytes. However, the length of OPT header varies with forwarding path length n, with the formulation as 52 + 16(n + 1). Table I shows the CO of PPV and OPT with different path lengths. Specifically, PPV has 43.24% CO of OPT with n = 5 hops (average AS-level path length [25]), and 23.19% and 16.49% CO of OPT with n = 13 hops and n = 20 hops (average and longest router-level path length [26]).

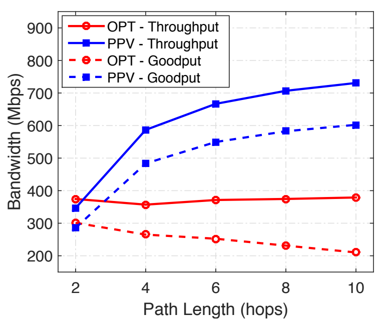
TABLE I
COMMUNICATION OVERHEAD COMPARISON.

	Communication overhead			Communication overhead ratio (n=13)		
	n=5 hops	n=13 hops	n=20 hops	256 B	512 B	1024 B
PPV	64 B	64 B	64 B	25.00%	12.50%	6.25%
OPT	148 B	276 B	388 B	100%	53.91%	26.95%

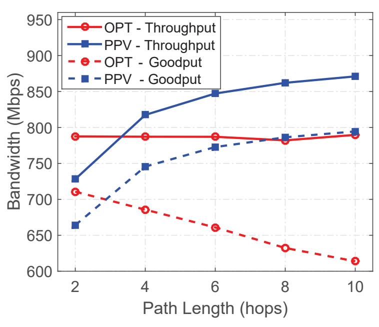
We define CO ratio Υ as the proportion between CO and the entire packet size. For large packets of 1024 bytes, Υ_{PPV}=$\frac{64}{1024}$=6.25% and this is independent of path length. However, Υ_{OPT}=$\frac{52+16(n+1)}{1024}$, which becomes higher as the path length increases. With n = 13 hops, Υ_{OPT} = 27.13%, worse than Υ_{PPV} = 6.25%. More seriously, for n = 20 hops, OPT incurs 37.11% CO, while PPV only introduces a constant Υ_{PPV} = 6.25%. For smaller packets of 256 bytes, Υ_{PPV} = $\frac{64}{256}$=25.00% and Υ_{OPT} = $\frac{52+16(n+1)}{256}$. Worse still, when the forwarding path length exceeds 12 hops, Υ_{OPT} is 100%.



(a) Packet size : 256 Bytes



(b) Packet size : 512 Bytes



(c) Packet size : 1024 Bytes

Fig. 6. The relationship between router's forwarding efficiency (throughput and goodput) and path length in the scenarios of different packet sizes.

B. Network performance

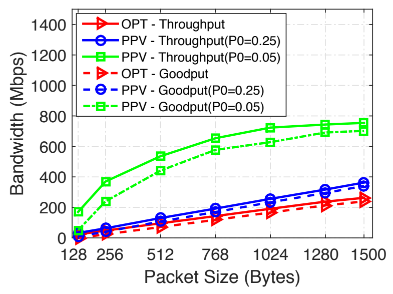
By analyzing the throughput and goodput, we evaluate the network performance of PPV. To compute goodput, we only consider the packet payload, subtracting IP/TCP header and PPV/OPT header from the entire IP packet. We run the experiment for at least 100 times when routers (destination) forward (receives) 10^6 packets for computing the throughput and the goodput. As for the basic probability P_0, we set it as the value of standard probability (*SP*), *i.e.*, $P_0 = 1/n$. We evaluate the performance of PPV and OPT with different packet sizes from 256 bytes to 1024 bytes by configuring the interface Maximum Transmission Unit (MTU) sizes. Due to $Q_1 = Q_2 = ... = Q_n = P_0$, routers at different locations have a same computation overhead. Thus, we can just evaluate the performance of any one router. In this case, different path lengths only bring different *SP*, illustrating we just adjust the value of *SP* to meet the path length variation.

Router performance. In order to evaluate router overhead, we implement a router prototype for PPV and OPT using the Click Modular Router, a flexible and configurable modular software router [30]. The system running the Click Router is an Ubuntu Linux 12.04, with Intel(R) Core(TM) i5-4590, CPU @ 3.30 GHz, 16.0 GB memory and NIC 1000 Mbps. With the help of iperf [31], we used a personal computer (Intel(R) Core(TM) i5-4200U, CPU @ 1.60 GHz/2.30 GHz, 12.0 GB memory) as the source to send packets to the NIC at a maximum rate of 1000 Mbps. The Click Router takes packets from NIC and processes them according to PPV or OPT protocol. Then it forwards the packets to D. During this process, we evaluate router performance by calculating its throughput and goodput for different packet sizes and path lengths. Fig. 6 shows the evaluation for PPV and OPT performance, where we can observe the following results. i) PPV outperforms OPT in terms of throughput and goodput in all but the smallest path lengths. The improvement in PPV is because only two neighbor routers (instead of all in OPT) perform packet marking with MAC operation for each forwarded packet. ii) With increasing path lengths, PPV introduces a better performance, while OPT brings about constant throughput and decreased goodput (described shortly).

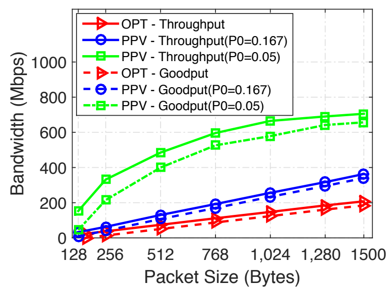
From OPT, we can know an OPT router's operation is independent from the path length, resulting in an almost constant throughput with the fixed packet size. Besides, an OPT router's goodput gradually decreases due to the increased communication overhead with incremental path lengths. Therefore, its goodput decreases when the path length increases. In contrast, the performance of a PPV router gets better as the path length increases as PPV router R_i has three, mutually exclusive, actions to either: i) insert its marking M_i into MF_1 and update MVF, with the probability $Q_i = P_0 = 1/n$; ii) write MF_2 as M_i and then update MVF, with the probability $Q_i = P_0 = 1/n$; iii) directly forward the packets to next hop, with the probability $(1 - Q_i - Q_{i-1}) = (1 - 2/n)$. With increasing path lengths, PPV router tends to carry out action iii), incurring less latency for packets process. Thus, the throughput and goodput of PPV become increasingly higher with larger path lengths. Additionally, PPV's constant communication overhead also improves the goodput compared to OPT as the throughput increases. With regard to numerical magnitude, PPV actions i) and ii) make PPV router perform a MAC operation twice the number of times as OPT router. In this case, PPV router's larger overhead in creating PPV header, compared to OPT router, decreases PPV's benefit when the path length is two hops. However, when the path length is larger than two hops, there is a probability (1 - $2/n$) for PPV router to perform action iii), bring a higher throughput and goodput than OPT.

Destination performance. We implement Click Modular Router to forward received packets to D via a NIC. D supports PPV and OPT running on Windows Server 2008, which has Intel(R) Xeon(R), CPU E5-2620 v3 @ 2.40 GHz (2 processors) and 32.0 G memory and a 1000 Mbps NIC.

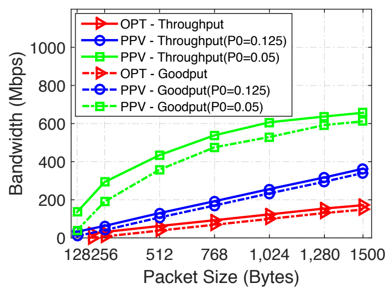
When evaluating D's performance, we analyze the throughput and goodput for PPV and OPT with different path length and packet size. Furthermore, we evaluate the performance at D with $P_0 = 0.05$ and $P_0 = 1/n$. From (a) to (d) in Fig. 7, we observe: i) PPV has higher throughput than OPT, because of PPV's fewer MAC operation (5 times) than OPT's ((n + 1) times) at D; ii) PPV has higher goodput than OPT due to PPV's higher throughput and constant communication overhead; iii) When P_0 is set to standard probability, i.e., $P_0 = 1/n$, PPV overhead is essentially constant at different packet sizes, illustrating the independence between path length and the performance. In contrast, OPT performs worse as the path length increases, because of the increased computational complexity; iv) With $P_0 = 0.05$, PPV has an improved throughput and goodput, compared to PPV with $P_0 = 1/n$ and is better than



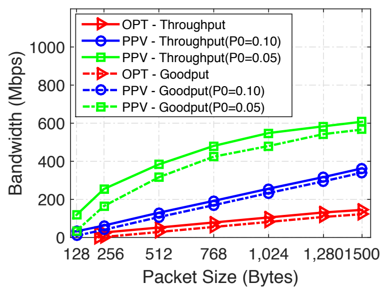
(a) The destination performance for n = 4 hops



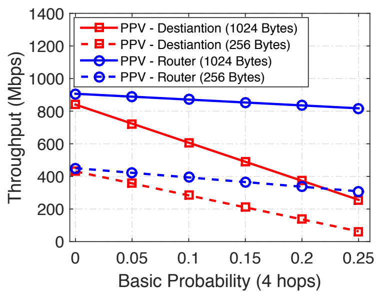
(b) The destination performance for n = 6 hops



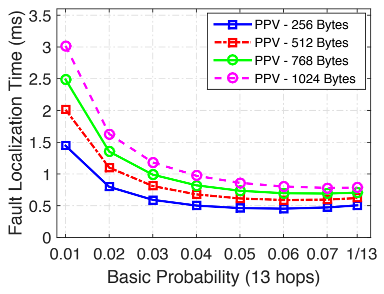
(c) The destination performance for n = 8 hops



(d) The destination performance for n = 10 hops



(e) Throughput *vs.* P_0 for different entities.



(f) T_r *vs.* P_0 for different packet size.

Fig. 7. The destination performance in terms of throughput, goodput and fault localization time with different packet sizes, path length and basic probabilities.

OPT. In the latter case, an empty marking field can appear on a PPV header with the probability (1 - $n{\cdot}P_0$). Reducing P_0 thus increases the number of empty marking fields, which lowers average time for destination's verification for one packet.

With the change of P_0, we will next analyze the influence on the performance of PPV. As P_0 is varied, routers and destination will have different throughputs, just as Fig. 7(e) shows. We respectively evaluate the throughputs of PPV and OPT in the Click Module Router and destination host for 256 bytes and 1024 bytes packet sizes. From Fig. 7(e), we see that the increased P_0 can lower the throughput of PPV for different packet sizes, because routers tend to directly forward the packets instead of performing the marking calculation, and at D it is less overhead to receive an empty marking field in a PPV header. However, the degree of the effect differs between routers and D, because the probability (1 - $n{\cdot}P_0$) of D's receiving empty marking field is more dominant than the probability (1 - $2P_0$) that a router directly forwards packets.

C. Fault Localization Time

In this paper, we use fault localization time T_r to evaluate the time for reconstructing Φ and localize the fault. Actually, once Φ is constructed, D can employ Algorithm 2 to localize the fault. T_r is relevant to both the convergence time T_c, illustrating the required number of packets to reconstruct Φ, and D's performance, which implies the rate of handling packets at D. Combining the analysis of T_c (Section IV-E) and D's performance, we analyze the relationship between T_r and P_0 at D host when the path length is almost the average value of the Internet, *i.e.*, n = 13 hops, as Fig. 7(f) shows.

We respectively evaluate T_r for the packet sizes of 256 bytes, 512 bytes, 768 bytes and 1024 bytes, which is from smaller packets to larger packets. We learn that the smaller packet, *e.g.*, 256 bytes, requires the less T_r for localizing the fault than the larger packet, *e.g.*, 1024 bytes, because small packets require less time for transmission under the same T_c. When P_0 takes the value of the standard probability, *i.e.*, P_0 = 1/13, 0.50 ms $\sim$ 0.80 ms will be required to locate the fault for different packet sizes. For the packet size of 256, 512, 768 and 1024 bytes, P_0 = 1/13 can bring about the fault localization time of 506.3 μs, 620.3 μs, 706.8 μs and 784.4 μs.

VII. Related Work

Secure routing and forwarding. The security of routing and forwarding is a vital component to ensure the authenticity of the Internet's routing infrastructure [1] [10] [19] [32] [33] [34] [35]. S-BGP can address the vulnerabilities and security requirements associated with BGP, which consumes a significant amount of router resources [1]. so-BGP cannot only authorize the integrity of packets, but can also mitigate various network-based attacks deriving from malicious insertion or misconfiguration [10]. IRV can validate the reliability of the announced messages at the cost of adding a new infrastructure, bringing about the challenges of maintenance and migration [33]. In contrast, PPV can lessen the burden of packets and improve the performance of intermediate routers using probabilistic packet marking.

Source and path verification. Tiffany Hyun-Jin Kim *et al.* [2] ensure source and path verification through the Origin and Path Trace (OPT) protocol. OPT can introduce lightweight routers for packet verification. Jad Naous *et al.* [3] present a Path Verification Mechanism (PVM) to address the verification for both source and path, checking the packet's supposed path and verifying the packets have passed all previous routing nodes on the path in the correct order. Hao Cai *et al.* [15] introduce a new protocol, OSP, to avoid the high computational cost of cryptographic operations, which uses a set of orthogonal sequences as credentials to a desired level of the accelerated verification in each router.

Fault localization. ShortMAC [22] leverages packet counts and content to identify the illegal network links, which achieves high authentication efficiency. DynaFL [36] achieves fault localization in datacenter networks, which has high availability for dynamic traffic patterns. Faultprints [11] can firstly localize the fault at the granularity of AS (inter-domain) level with high performance and lower overhead. However, they all require each router to pay for extra storage overhead.

IP traceback. IP traceback solutions can contribute to protecting the destination from DDos attacks, source spoofing and localizing the faulty source. Pi, short for Path Identifier, employs a new packet marking method to enable the destination to identify each packet traveling along the same path [17]. Abraham Yaar *et al*. propose the stackPi marking, containing stack-based marking and write-ahead marking, which is a novel packet marking mechanism for DDoS and IP spoofing defense [18]. Stefan Savage *et al*. introduce a universal traceback method which is based on probability packet marking to help the victim identify the attack traffic [16]. However, in their mechanisms, all entities are supposed credible and secure, which cannot suit the localization of faulty routers.

VIII. Conclusion

In this paper, we design, analyze, implement and evaluate PPV, a highly-efficient data-plane verification for source authenticity and path compliance, which performs a trade off between security and overhead. PPV employs probabilistic packet marking in entities such that it allows the destination to verify packet source and packet forwarding paths. Meanwhile, PPV can efficiently localize offending entities by reconstructing the actual forwarding paths. We make an security analysis to demonstrate the security of PPV against source spoofing and path inconsistency. We also demonstrate the high-efficiency of PPV by real experiments. PPV outperforms the state-of-the-art schemes in the following aspects. First, PPV effectively decreases the packet forwarding overheads and thus improves the throughput and goodput. Second, PPV is capable of efficient fault localization. We hope that the high-efficiency property of PPV can become a fundamental primitive to build highly secure and readily deployed security protocols.

Acknowledgments

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