Advanced and Authenticated Marking Schemes for IP Traceback

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Abstract—**Defending against distributed denial-of-service attacks is one of the hardest security problems on the Internet today. One difficulty to thwart these attacks is to trace the source of the attacks because they often use incorrect, or spoofed IP source addresses to disguise the true origin. In this paper, we present two new schemes, the Advanced Marking Scheme and the Authenticated Marking Scheme, which allow the victim to traceback the approximate origin of spoofed IP packets. Our techniques feature low network and router overhead, and support incremental deployment. In contrast to previous work, our techniques have significantly higher precision (lower false positive rate) and lower computation overhead for the victim to reconstruct the attack paths under large scale distributed denial-of-service attacks. Furthermore the Authenticated Marking Scheme provides efficient authentication of routers' markings such that even a compromised router cannot forge or tamper markings from other uncompromised routers.**

Keywords— **IP traceback, distributed denial-of-service attacks, DDoS, DoS, packet-marking traceback.**

I. Introduction

DENIAL-OF-SERVICE (DoS) attacks pose an increasing threat to today's Internet [1]. Even more concerning, automatic attacking tools (such as Tribal Flood Network (TFN), TFN2K, Trinoo, and stacheldraht) allow teenagers to launch widely distributed denial-of-service (DDoS) attacks with just a few keystrokes [2]. Some nice analysis of DDoS and the tools can be found in [3], [4]. Just to name one of the many cases, in February 2000, several high-profile sites including Yahoo, eBay, and Amazon were brought down for hours by DDoS attacks [2]. And real DDoS attacks are often mounted from hundreds or even thousands of hosts. A serious problem to fight these DoS attacks is that attackers use incorrect, or spoofed IP addresses in the attack packets and hence disguise the real origin of the attacks. Due to the stateless nature of the Internet, it is a difficult problem to determine the source of these spoofed IP packets, which is called the *IP traceback* problem.

While many IP traceback techniques have been proposed, they all have shortcomings that limit their usability in practice (we discuss more details on related work in section V). One promising solution, recently proposed by Savage et al., is to let routers probabilistically mark packets with partial path information during packet forwarding [5]. The victim then reconstruct the complete paths after receiving a modest number of packets that contain the marking. We refer to this type of approach as the *IP marking approach*. This approach has a low overhead for routers and the network and supports incremental deployment. Savage et al. propose the *Fragment Marking Scheme*, which we refer to as FMS, for their IP marking approach. Unfortunately, as we will show in our theoretical analysis in appendix A and simulation results in section III-C, this approach has a very high computation overhead for the victim to reconstruct the attack paths, and gives a large number of false positives when the denial-of-service attack originates from multiple attackers. For example, this approach can require days of computation to reconstruct the attack paths and give thousands of false positives even when there are only 25 distributed attackers. This approach is also vulnerable to compromised routers. If a router is compromised, it can forge markings from other uncompromised routers and hence lead the reconstruction to wrong results. Even worse, the victim will not be able to tell a router is compromised just from the information in the packets it receives.

In this paper we present two new IP marking techniques to solve the IP traceback problem: The Advanced Marking Scheme and the Authenticated Marking Scheme. Our approach has the same low network and router overhead as FMS proposed by Savage et al. [5], yet our approach is much more efficient and accurate for the attacker path reconstruction under DDoS. In particular, our approach can reconstruct the attacker path within seconds and has a low false positive rate. Furthermore, our Authenticated Marking Scheme supports efficient authentication of routers' markings. This prevents a compromised router from forging other uncompromised routers markings. Our schemes also support incremental deployment and allow the victim to reconstruct the attack paths even after the attack has completed.

This paper is organized as follows. We review background information and highlight the main challenges of the IP marking approach in section II. Section III introduces our new Advanced Marking Schemes and shows theoretical analysis and experiment results which indicate our Advanced Marking Schemes are efficient and accurate even in the presence of large scale DDoS attacks. In section IV, we describe our new Authenticated Marking Scheme that provides efficient authentication of routers' markings. Finally we discuss some practical issues and the related work in section V, and conclude in section VI.

II. Background and Challenge

A. Definitions

The directed acyclic graph (DAG) rooted at V in figure 1 represents the network as seen from a victim V and a distributed

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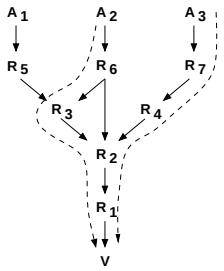

Fig. 1. Upstream router map from victim

denial-of-service attack from A_2 and A_3. V could be either a single host under attack or a network border device such as a firewall representing many such hosts. Nodes R_i represent the routers, which we refer to as *upstream* routers from V, and we call the graph the *map of upstream routers from* V. For every router R_i, we refer to the set of routers that immediately before R_i in the graph as the *children* of R_i, e.g. R_3, R_6 and R_4 are R_2's children. The leaves $\{A_i\}$ represent the potential *attack origins*, or *attackers*. The *attack path* from A_i is the ordered list of routers between A_i and V that the attack packet has traversed, e.g. the two dotted lines in the graph indicate two attack paths: (R_6, R_3, R_2, R_1) and (R_7, R_4, R_2, R_1). The *distance* of R_i from V on a path is the number of routers between R_i and V on the path, e.g. the distance of R_6 to V in the path (R_6, R_3, R_2, R_1) is 3. The *attack graph* is the graph composed of the attack paths, e.g., the attack graph in the example will be the graph containing the two attack paths (R_6, R_3, R_2, R_1) and (R_7, R_4, R_2, R_1). And we refer to the packets used in DDoS attacks as *attack packets*. We call a router *false positive* if it is in the reconstructed attack graph but not in the real attack graph. Similarly we call a router *false negative* if it is in the true attack graph but not in the reconstructed attack graph. We call a solution to the IP traceback problem robust if it has very low rate of false negatives and false positives.

B. IP Marking with Edge Sampling

The basic idea of the IP marking approach is that routers probabilistically write some encoding of partial path information into the packets during forwarding. A basic technique, the *edge sampling algorithm*, is to write *edge* information into the packets [5]. This scheme reserves two static fields of the size of IP address, *start* and *end*, and a static *distance* field in each packet. Each router updates these fields as follows.

Each router marks the packet with a probability q. When the router decides to mark the packet, it writes its own IP address into the start field and writes zero into the distance field. Otherwise, if the distance field is already zero which indicates its previous router marked the packet, it writes its own IP address into the end field, thus represents the edge between itself and the previous routers. Finally, if the router doesn't mark the packet, then it always increments the distance field. Thus the distance field in the packet indicates the number of routers the packet has traversed from the router which marked the packet to the victim. The distance field should be updated using a saturating addition, meaning that the distance field is not allowed to wrap. The mandatory increment of the distance field is used to avoid spoofing by an attacker. Using such a scheme, any packet written by the attacker will have distance field greater than or equal to the length of the real attack path.

The victim can use the edges marked in the attack packets to reconstruct the attack graph. For each attack path with distance d, the expected number of packets needed to reconstruct the path is bounded by $\frac{ln(d)}{q(1-q)^{d-1}}$.

C. Overloading the IP Identification Field

The edge sampling algorithm requires 64 bits for the start and end field and another few bits for the distance field in every IP packet. We could store these bits in an IP option, but this is impractical because appending additional data to a packet on the fly is expensive and may lead to fragmentation. We could also send it in a separate packet, but this adds more network and router overhead. A more efficient solution is to overload the 16-bit IP Identification field used for fragmentation in the IP header. Recent measurements suggest that less than 0.25% of packets are fragmented [6]. We refer to [5] for discussions on practical issues about overloading the IP Identification field.

D. Limitation of FMS and Challenge

In order to use the 16-bit IP Identification field to store the IP markings, we need an encoding scheme to reduce the storage requirements in each packet.

The FMS encoding scheme splits each router's IP address and redundancy information into eight fragments and probabilistically marks the IP packet with one of the eight fragments [5]. This encoding scheme works well with just a single attacker. But in case of a distributed denial-of-service attack, FMS suffers from two main problems:

- High computation overhead, because it needs to check a large number of combinations of the fragments,
- Large number of false positives, because the redundancy check is insufficient and the false positives at a closer distance to the victim can cause even more false positives further away from the victim.

For example, as shown in our simulation results (section III-C), even in case of a DDoS from 25 distributed attacker sites, FMS takes days to reconstruct the attack graph and results in thousands of false positives. We also include a more detailed theoretical analysis in appendix A and simulation results in section III-C.

FMS also suffers from the fact that it is not robust against a compromised router. Even worse, a victim cannot even tell that a router has been compromised merely from the information in the packets received.

The main challenge is to design an efficient, accurate, and authenticated encoding scheme for IP marking that only uses the 16 bits available from the IP identification field.

III. Advanced Marking Schemes

In this section, we describe our Advanced Marking schemes, in which we use new encoding schemes that are efficient and accurate even for DDoS attacks originating from over 1000 simultaneous attackers. We observe that if the victim knows the map of its upstream routers, it does not need the full IP address in the

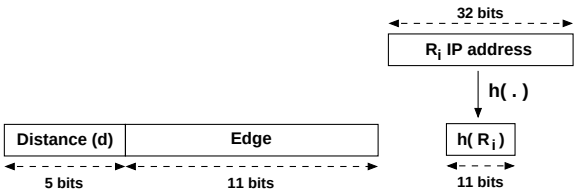

Fig. 2. Encoding in Advanced Marking Scheme I

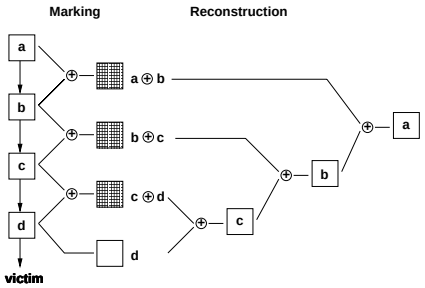

Fig. 3. XOR Encoding

packet marking to reconstruct the attacking graph, and hence the marking scheme can be more communication and computation efficient. For our marking schemes, we assume the victim has a map of its upstream routers, denoted as G_m. G_m is a DAG with the victim as the root. We show in section V-A that this assumption is practical.

A. Advanced Marking Scheme I

In the basic approach, we use a similar marking scheme as FMS, but instead of encoding the IP address of a router R_i into eight fragments, we simply encode its hash value, $h(R_i)$, as figure 2 shows. In this scheme, we divide the 16-bit IP Identification field into a 5-bit *distance* field and a 11-bit *edge* field. Note that 5 bits can represent 32 hops which is sufficient for almost all Internet paths [7], [8], [9].

Marking.. Figure 4 describes the marking procedure of Advanced Marking Scheme I. Note that we actually use two independent hash functions, h and h', in the encoding of the routers' IP addresses. h and h' both have 11-bit outputs. Every router marks a packet with a probability q when forwarding the packet. If a router R_i decides to mark the packet P, it writes $h(R_i)$ into the edge field and 0 into the distance field in packet P. Otherwise, if the distance field is 0 which implies its previous router has marked the packet, it XORs $h'(R_i)$ with the edge field value and overwrites the edge field with the result of the XOR. The router always increments the distance field if it decides not to mark the packet. The XOR of two neighboring routers encode the edge between the two routers of the upstream router map. The edge field of the marking will contain the XOR result of two neighboring routers, except for samples from routers one hop away from the victim. Because $a \oplus b \oplus a = b$, we could start from markings from the routers one hop away from the victim, and then hop-by-hop, decode the previous routers, as shown in figure 3. The reason to use two independent hash functions is to distinguish the order of the two routers in the XOR result.[1]

Reconstruction.. Figure 4 describes the reconstruction procedure. Intuitively, to reconstruct the attack paths, the victim uses the upstream router map G_m as a road-map and performs a breadth-first search from the root. Let's denote the set of edge fields marked with a distance d as Ψ_d (do not include duplicates). At distance 0, the victim enumerates all the routers one hop away from itself in G_m and checks which routers have the hash value of their IP addresses, $h(R_i)$, matched with the edge fields in Ψ_0, and denotes the set of matched IP addresses as S_0. Therefore S_0 is the set of routers one hop away from the victim in the reconstructed attack graph. S_d denotes the set of routers at distance d to the victim in the reconstructed attack graph. Then for each edge x in Ψ_{d+1}, and for each element y in S_d, the victim computes $z = x \oplus h'(y)$. The victim then checks whether any child R_i of y in G_m has the hash value of its IP address, $h(R_i)$, equal to x. If the victim finds a matched IP address R_u, then it adds R_u to the set S_{d+1} (initially S_{d+1} is empty). The victim repeats the steps until it reaches the maximal distance marked in the packets, denoted as $maxd$. Thus, the victim reconstructs the attack graph.

Analysis.. Assume a DDoS attack, and let $|M_d|$ denote the number of routers in the attack graph at distance d from the victim. Let t_y denote the in-degree of element y in S_{d-1} (the number of y's children) in G_m, and recall that $|\Psi_d|$ is the number of unique edge segments received by the victim with the distance field marked as d. Because the hash value is 11 bits, the expected number of false positives among y's children in G_m is $t_y \cdot |\Psi_d|/2^{11}$. If we assume that the hash functions are good random functions, $\mathsf{E}(|\Psi_d|) = (1 - (1 - 1/2^{11})^{|M_d|}) \cdot 2^{11}$. For example, when $t_y = 32, |M_d| = 64$, the expected number of false positives among y's children in G_m is less than 1. The total expected number of false positives is approximately the sum of the expected numbers of false positives in y's children in G_m for all y in the sets $\{S_d\}_{0 \le d \le maxd}$. In subsection III-C, we see that this scheme can already sustain DDoS attack from 50 distributed attacker sites, which is twice as high as FMS.

The computational complexity of this scheme is also much lower than the Fragment Marking scheme, $O(\sum_d |S_d| \cdot |\Psi_{d+1}|)$ instead of $O(\sum_d |S_d| \cdot |\Psi_{d+1}|^8)$. Also, given the same marking probability q, this scheme needs less than one eighth of the packets as the FMS to reconstruct the attack graph.

B. Advanced Marking Scheme II

Although the Advanced Marking Scheme I is more efficient and accurate than FMS in case of DDoS, it still gives false positives when there are more than about 60 distributed attacker sites. The reason is that the 11-bit hash value is not sufficient to avoid collision when there are many routers at the same distance to the victim in the attack graph. In order to be more robust against larger scale DDoS, we further extend the scheme. In particular, instead of using just two hash functions, we use two sets of independent hash functions. The intuition is that the probability of any false positive a to have the same hash value as a router b for one hash function h_1 is $1/2^{11}$, and the probability of a to have the same hash values as b for m independent hash functions is $(1/2^{11})^m = 1/2^{11 \cdot m}$.

[1] Given a collision-resistant hash function g, we can simply implement the two independent hash functions in a standard way: $h(x) = g(\langle 0, x \rangle), h'(x) = g(\langle 1, x \rangle)$, where $\langle \_, \_ \rangle$ means concatenation.

Marking procedure at router R_i:
  for each packet P
    let u be a random number from $[0, 1)$
    if $u \leq q$ then
      P.distance $\leftarrow$ 0
      P.edge $\leftarrow h(R_i)$
    else
      if (P.distance == 0) then
        P.edge $\leftarrow$ P.edge $\oplus\, h'(R_i)$
      P.distance $\leftarrow$ P.distance + 1

Reconstruction procedure at victim v:
  let S_d be empty for $0 \leq d \leq$ *maxd*
  for each child R of v in G_m
    if $h(R) \in \Psi_0$ then
      insert R into S_0
  for *d*:= 0 to *maxd* $- 1$
    for each y in S_d
      for each x in Ψ_{d+1}
        $z = x \oplus h'(y)$
          for each child u of y in G_m
            if $h(u) = z$ then
              insert u into S_{d+1}
  output S_d for $0 \leq d \leq$ *maxd*

Fig. 4. Advanced Marking Scheme I

Note that a standard way to generate a set of 2^a independent hash functions $\{h_i(.)\}_i$ is to use one hash function, i.e. g, and let $h_i(x) = g(\langle i, x\rangle)$, where i is an a-bit index, and $\langle \_, \_ \rangle$ represents concatenation. Suppose we use 2^w independent hash functions in this scheme. Every time when a router decides to mark the packet, it would choose one of the 2^w hash functions for the encoding. And when the victim reconstructs the attack graph, it would need to know which hash function the router used to mark each individual packet.

One approach is to use some packet-specific data to determine which hash function the router should choose and to indicate to the victim which hash function the router has used. For example, for a packet P containing source IP address $\mathsf{sourceIP}$, the encoding of the router IP R_i could be $g(\langle f(\mathsf{sourceIP}), R_i\rangle)$, where f is a function mapping from 32 bits to w bits. $f(x)$ could be simply the first w bits of x, or a better solution, be another independent hash function. Thus, with packets containing different source IP addresses, the victim can hopefully get markings of each router with 2^w independent hash functions. Unfortunately this approach is not robust against the countermeasure of attackers. First, the attackers could simply use the same spoofed source IP address (this approach is not very effective since if the attacker uses the same source IP address, the victim can easily block it). Second, the attackers could carefully compute the source IP addresses such that they all hash into the same w bits. Since w is normally small for efficiency reason, the second countermeasure is practical. In this case, the packets marked by the same router will only be marked with hash values from one hash function, instead of a set of 2^w independent hash functions as mentioned before.

Therefore, we use another approach where we use an explicit *flag* field to indicate which hash function the router has used for the marking. In particular, we divide the overloaded IP Identification field into a w-bit flag field, *fID*, a $(11 - w)$-bit edge field, and a 5-bit distance field. Figure 5 shows an example of this approach for $w = 3$. With a given fID, the encoding of a router R_i is simply $h(\langle \mathsf{fID}, R_i\rangle)$. Thus different fIDs indicate

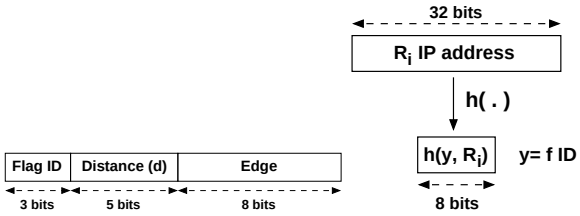

Fig. 5. Encoding for Advanced Marking Scheme II

different independent hash functions. When a router R_i decides to mark a packet, it chooses a random number x of w bits and write it in the flag field and use $g(\langle x, R_i\rangle)$ as its IP address encoding, as figure 5 shows. The rest of the scheme is similar to the Advanced Marking scheme 1. Figure 6 shows a more detailed description of the scheme in the case of $w = 3$.

Advanced Marking Scheme II at router R_i:
  for each packet P
    let u be a random number from $[0, 1)$
    if $u \leq q$ then
      let x be a random integer from $[0, 7)$
      P.fID $\leftarrow x$
      P.distance $\leftarrow$ 0
      P.edge $\leftarrow g(\langle x, R_i\rangle)$
    else
      if (P.distance == 0) then
        P.edge $\leftarrow$ P.edge $\oplus\, g'(\langle$P.fID, $R_i\rangle)$
      P.distance $\leftarrow$ P.distance + 1
Reconstruction procedure at victim v:
  let S_d be empty for $0 \leq d \leq$ *maxd*
  for each child R of v in G_m
  let *count* = 0
    for *l*:= 0 to $2^w - 1$
      if $g(\langle l, R\rangle) \in \Psi_{0,l}$ then
        $count = count + 1$
    if $count > m$ then
      insert R into S_0
  for *d*:= 0 to *maxd* $- 1$
    for each y in S_d
      for each child u of y in G_m
        let *count* = 0
        for *l*:= 0 to $2^w - 1$
          for each x in $\Psi_{d+1,l}$
            $z = x \oplus g'(\langle l, y\rangle)$
            if $g(\langle l, u\rangle) = z$ then
              $count = count + 1$; break
        if $count > m$ then
          insert u into S_{d+1}
  output S_d for $0 \leq d \leq$ *maxd*

Fig. 6. Advanced Marking Scheme II

The reconstruction algorithm is similar to the Advanced Marking Scheme 1, except that here we use a threshold scheme. Recall that G_m denotes the map of upstream routers from the victim. Let's denote the set of unique edge segments marked with a distance d and flag ID l as $\Psi_{d,l}$. For a m-threshold scheme, a node u in G_m will only be considered as on an attack path if more than m of its hash values from the 2^w hash functions match the right markings in the attack packets. More details of the reconstruction procedure is described in figure 6.

Assume a DDoS attack where $|M_d|$ denotes the number of routers on the attack paths at distance d from the victim. Recall S_{d-1} denotes the set of routers at distance $d - 1$ to the victim in the reconstructed attack graph. For every element y in S_{d-1}, let t_y denotes the in-degree of y (the num-

ber of y's children) in G_m. Then in a 2^w-threshold scheme, the expected number of false positives among y's children is $t_y \cdot \prod_{1 \le l \le 2^w} \frac{|\Psi_{d,l}|}{2^{11-w}}$. Assume the hash functions are good random functions, $\mathsf{E}(|\Psi_{d,l}|) = (1-(1-1/2^{11-w})^{|M_d|}) \cdot 2^{11-w}$. For example, when $w = 3, t_y = 32, |M_d| = 128$, the expected number of false positives among y's children is less than 1. The total expected number of false positives is approximately the sum of the expected numbers of false positives in y's children in G_m for all y in the sets $\{S_d\}_{0 \le d \le maxd}$. In subsection III-C, we see that this scheme can sustain DDoS attack from over 1500 distributed attacker sites.

The computational complexity of this scheme is still $O(\sum_d |S_d| \cdot |\Psi_{d+1}|)$ instead of $O(\sum_d |S_d| \cdot |\Psi_{d+1}|^8)$ in FMS. Although in the case of $w = 3$, this scheme with threshold $m > 7$ needs about the same number of packets as FMS given the same marking probability q, this scheme has the advantage that it can already start reconstructing the attack graph when it only receives a fraction of the packets as needed in the Fragment Marking scheme, and the more packets it receives, the precision of the reconstructed attack graph simply increases.

C. Simulation Results

To test the behavior of these Advanced Marking schemes in real settings, we conduct an experiment on simulated attacks using a real traceroute dataset obtained from Lucent Bell Labs [10]. The traceroute dataset contains 709,310 distinct traceroute paths from a single source to 103,402 different destinations widely distributed over the entire Internet. In all the tests, we use the single source of the traceroute as the victim, and the whole traceroute dataset as the map of upstream routers from the victim. In each test, we randomly select a given number of destinations in the dataset as attackers. We then simulate the routers to mark the attack packets, and simulate the victim to reconstruct the attack graph using the markings in the packets. As indicated in the theoretical analysis, the number of false positives and computation time is related to the distribution of the number of routers $|M_d|$ at a distance d, $0 \le d \le maxd$, in the attack graph. Even with the same number of attackers, the distribution of $\{|M_d|\}_{0 \le d \le maxd}$ could be very different depending on the convergence of the attack paths. For most of the data points in the figures, we perform about 50–100 independent tests and compute the average of the result.

Figures 7 and 8 show the number of false positives of the Advanced Marking Scheme I and the Advanced Marking Scheme II with $w = 3$ and three different thresholds $m > 5, m > 6$ and $m > 7$. The Advanced Marking Scheme I can sustain DDoS attacks from fewer than 50 distributed attacker sites, while the Advanced Marking Scheme II with threshold $m > 5$ can sustain 500 distributed attacker sites with very few false positives, and with threshold $m > 6$ can sustain 1000 attacker sites. Finally, the Advanced Marking Scheme II with threshold $m > 7$ can be robust against DDoS with even 1500 distributed attacker sites and only has 20 false positives when there are 2000 attacker sites.

Figure 9 shows the time to reconstruct the attack graph by the victim after the victim has received all the packets needed (measured on a 500 MHz Pentium III Linux workstation). The

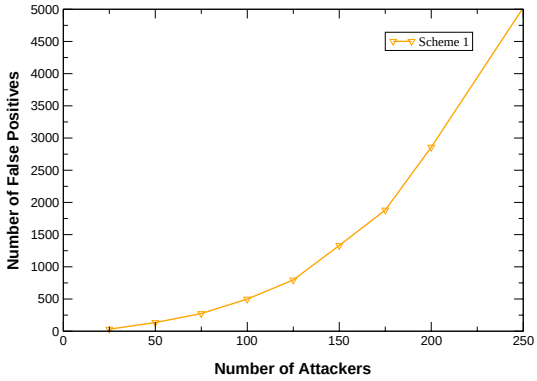

Fig. 7. False Positives for Advanced Marking Scheme I

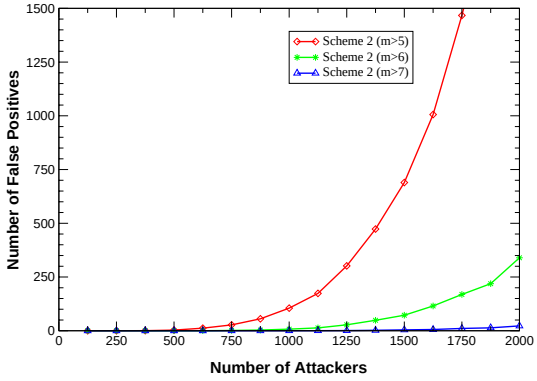

Fig. 8. False Positives for Advanced Marking Scheme II

Advanced Marking Scheme I took substantially longer as the number of attackers increase because it has many more false positives. For the Advanced Marking Scheme II, all three different thresholds took less than 100 seconds to reconstruct the attack graph even when there are 2000 distributed attacker sites.

For comparison purpose, we preform a similar simulation using FMS, shown in figures 10 and 11. With only 20 attackers, the scheme already outputs over 100 false positives and takes more than a day to reconstruct the attack graph. With 25 attackers, the scheme outputs thousands of false positives and cannot terminate within a week. Note that our timing information is based on a highly optimized implementation of FMS running on a 500 MHz Pentium III Linux workstation. So for simulations with more than 20 attackers, we compute the expected number of false positives and expected computation overhead using the formulas in our theoretical analysis (for details, see appendix A). The main reason for the dramatic increase of the number of false positives for FMS is because of a cumulative explosion effect – false positive routers at a distance i from the victim cause more false positives at distance $i + 1$ during the reconstruction.

We also tested the nubmer of packets required to reconstruct the attack graph. Figures 12 and 13 show the simulation result of the number of packets required to reconstruct paths of varying length with 95% probability in presence of only one attacker for the Fragment Marking Scheme and our Advanced Marking Schemes (with $w = 3$). Each data point is averaged over 100

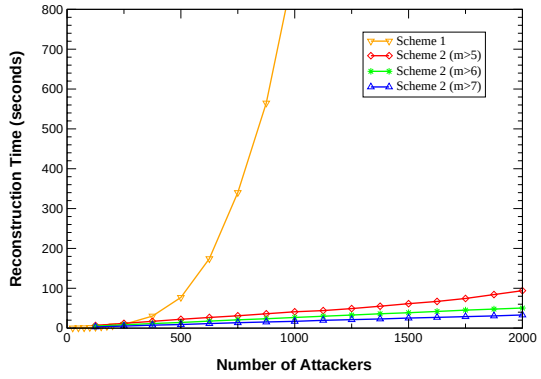

Fig. 9. Computation Overhead for Advanced Marking Schemes

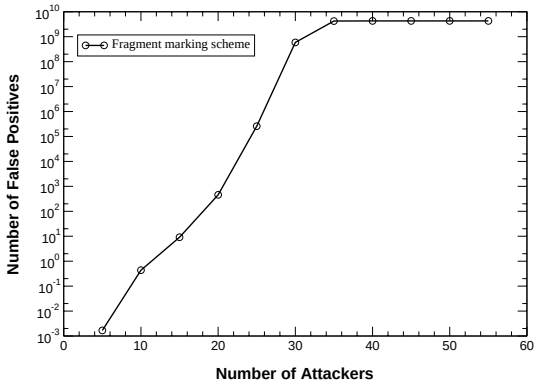

Fig. 10. False Positives for FMS

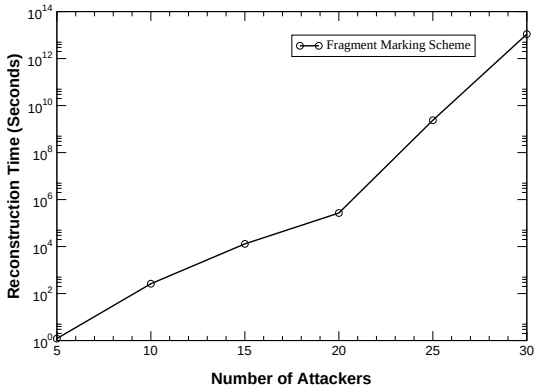

Fig. 11. Computation Overhead for FMS

independent random tests with an attacker at a certain distance from the victim. The marking probability is $q = 4\%$ in figure 12, and $q = 1\%$ in figure 13. As described in section III-B, FMS and the Advanced Marking Scheme II with $w = 3$ and threshold $m > 7$ require the same number of packets to reconstruct the attack paths, while the Advanced Marking Scheme II with $w = 3$ and threshold $m > 6$ and $m > 5$ require substantially fewer packets for the reconstruction. Hence the Advanced Marking Scheme has the advantage that it can already start reconstructing the attack graph with only a fraction of the packets needed by FMS. The more packets it receives, the attack graph simply becomes more accurate.

IV. Authenticated Marking Scheme

A fundamental shortcoming of the advanced marking schemes is that the packet markings are not authenticated. Consequently, a compromised router on the attack path could forge the markings of upstream routers. Moreover, the compromised router could forge the markings according to the precise probability distribution, preventing the victim from detecting and determining the compromised router by analyzing the marking distribution. To solve this problem, we need a mechanism to authenticate the packet marking. A straightforward way to authenticate the marking of packets is to have the router digitally sign the marking. However, digital signatures have two major disadvantages. First, they are very expensive to compute (a 500 MHz Pentium can only compute on the order of 100 1024-bit RSA signatures per second). Secondly, the space overhead is large (128 bytes for a 1024-bit RSA signature).

We propose a much more efficient technique to authenticate the packet marking, the Authenticated Marking Scheme. This technique only uses one cryptographic MAC (Message Authentication Code) computation per marking, which is orders of magnitude more efficient to compute (i.e., HMAC-MD5 is three to four orders of magnitude more efficient than 1024-bit RSA signing) and can be adapted so it only requires the 16-bit overloaded IP identification field for storage.

A. Step 1: Authentication with a MAC

Message Authentication Codes (MAC) such as HMAC [11] are commonly used for two-party message authentication. Two parties can share a secret key K. When party A sends a message M to party B, A appends the message with the MAC of M using key K. When B receives the message, it can check the validity of the MAC. A well-designed MAC guarantees that nobody can forge a MAC of a message without knowing the key. MAC computation is very efficient, e.g. a fast workstation can compute around $300,000$ 8-byte HMAC-MD5 per second, and around $3,000,000$ CBC-MAC with RC5 (measured on a 500 MHz Pentium III Linux workstation).

Let f denote a MAC function and f_K the MAC function using key K. If we assume that each router R_i shares a unique secret key K_i with the victim, then instead of using hash functions to generate the encoding of a router's IP address, R_i can apply a MAC function to its IP address and some packet-specific information with K_i. Because a compromised router still does not know the secret keys of other uncompromised routers, it cannot forge markings of other uncompromised routers. The packet-specific information is necessary to prevent a replay attack, because otherwise, a compromised router can forge other routers markings simply by copying their marking into other packets. We could use the entire packet content in the MAC computation, i.e. encode R_i as $f_{K_i}(\langle \mathsf{P}, R_i \rangle)$. But for efficiency, it might also be sufficient to just use the source and destination IP addresses in the packet, i.e. encode R_i as $f_{K_i}(\langle \mathsf{sourceIP}, \mathsf{destinationIP}, R_i \rangle)$. In this case, a compromised router might still be able to forge a marking in a packet by using the same source IP address, but in this case, the vic-

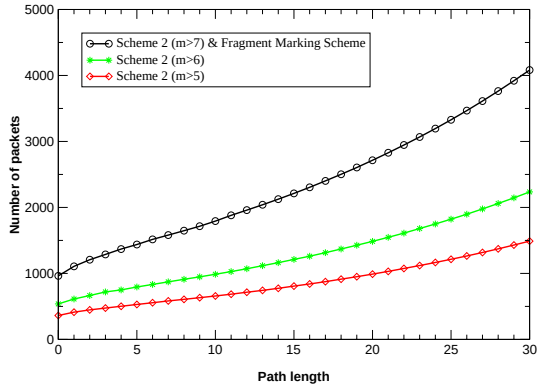

Fig. 12. Number of Packets Required for Reconstruction ($q = 4\%$)

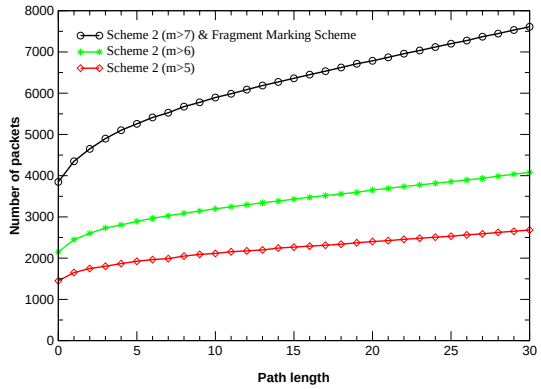

Fig. 13. Number of Packets Required for Reconstruction ($q = 1\%$)

tim can block traffic coming from this source IP address. (Also the extended scheme in step 2 can reduce the possible number of source IP addresses that the compromised router could use to replay.) Besides the change of using a MAC function with secret keys instead of publicly available hash functions, the marking and reconstruction procedure is similar to the Advanced Marking schemes.

B. Step 2: Using Time-Released Key Chains

Although Step 1 can provide router authentication, it is obviously impractical because it requires each router to share a secret key with each potential victim. To solve this problem, we extend the scheme by using the time-released keys authentication scheme. A similar scheme was proposed by Perrig et al. for multicast source authentication [12].

The basic idea is that each router R_i first generates a sequence of secret keys, $\{K_{j,i}\}$ where each key $K_{j,i}$ is an element of a hash chain. By successively applying a one-way function g (e.g. a cryptographic hash function such as MD5 [13]) to a randomly selected seed, $K_{N,i}$, we can obtain a chain of keys, $K_{j,i} = g(K_{j+1,i})$. Because g is a one-way function, anybody can compute forward (backward in time), e.g. compute $K_{0,i}, \ldots, K_{j,i}$ given $K_{j+1,i}$, but nobody can compute backward (forward in time), e.g. compute $K_{j+1,i}$ given only $K_{0,i}, \ldots, K_{j,i}$, due to the one-way generator function. This is similar to the S/Key one-time password system [14].

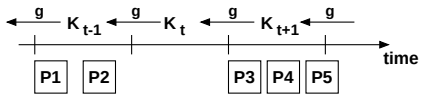

Fig. 14. Authenticated Marking Using a Time-Released Key Chain at a Router.

Each router R_i commits to the secret key sequence through a standard commitment protocol, e.g. by signing the first key of the chain $K_{0,i}$ with its private key, and publish the commitment out of band, e.g. by posting it on a web site. We assume that each router has a certified public key.

The time is divided into intervals (as shown later, the time interval needs to be sufficiently long, e.g. on the order of ten seconds). Each router R_i then associates its key sequence with the sequence of the time interval, with one key per time interval. In time interval t, the router R_i uses the key of the current interval, $K_{t,i}$, to mark packets in that interval. The marking scheme is the same as in Step 1, except that instead of using a shared secret key between R_i and the victim to compute the marking, the router uses $K_{t,i}$ as the key to compute the MAC. R_i will then reveal the key $K_{t,i}$ after a delay of δ_r after the end of the time interval t. The key disclosure time delay δ_r is on the order of a few time intervals, as long as it is greater than any reasonable round trip time on the Internet plus the maximum synchronization error between the router and the victim. The disclosure of the keys can be done out of band, e.g. published on a web-site.

Figure 14 shows an example of using a time-released secret key chain for the authenticated marking scheme. Note that because of the use of the key chain, the victim only needs to download the keys of the routers for the latest time interval and then it is able to compute all the keys for previous time intervals.

When the victim receives the marked packets, it saves the arrival time for each packet. Note that the victim and the routers need an approximate time synchronization. For the purpose of this approach, the time only needs to be loosely synchronized, e.g. the synchronization error may be on the order of multiple seconds. This level of approximate time synchronization is easy to achieve in practice. Please refer to [15], [12] for more details on time synchronization.

Before reconstructing the attack graph, the victim downloads the disclosed keys of the routers. Note that the victim does not need to download the keys of all routers at once. It starts from its nearest router to routers further away as necessary in the reconstruction process. For each marked packet, it first determines the sending time interval of the packet using its arrival time. Suppose the arrival time of the packet is T_a, the time synchronization between the victim and the router is $\pm\delta_s$, and the maximum transmission delay of the packet is δ_d. Thus, the actual sending time of the packet T_s is bounded as $T_a - \delta_s - \delta_d < T_s < T_a + \delta_s$. Therefore, if the length of the time interval is substantially longer than $2\delta_s + \delta_d$, the victim can determine the sending time interval of the marked packet with high probability. After determining the sending time interval of the marked packets, the victim can associate the right keys used to compute the MACs with the packets. It can then use a similar reconstruction algorithm as the Advanced Marking Schemes to reconstruct the attack graph.

Note that because we use the source IP address and differ-

ent keys over different time intervals in the computation of the encoding of router IP addresses, it has the same effect as using a set of independent hash functions as described before. So it is not necessary to use an explicit flag field as in the Advanced Marking Scheme 2 if we mainly consider DDoS attacks that last multiple time intervals.

V. Discussion

A. Mapping Upstream Routers

In previous sections, we show that the Advanced Marking Schemes and the Authenticated Marking Scheme are very efficient and accurate even in presence of large distributed denial-of-service attacks. But these marking schemes rely on the assumption that the victim has a map of upstream routers. In this subsection, we show that this assumption is reasonable and practical.

First, it is easy to obtain such a map of upstream routers for a victim. Standard tools exist for mapping, such as a tool based on traceroute from Lucent Bell Labs [10] and Skitter from CAIDA [9]. These tools can obtain the map of upstream routers from the victim to over 100,000 destinations per day.

Second, such a map does not need to have high accuracy and does not need to be very recent, as long as the attack graph is contained in this map. Furthermore, even if the victim does not have such a map before it is attacked by DDoS, it can obtain the map after the attack.

Another approach to get the upstream router map is to use our approach in conjunction with itrace [16]. During peace time the victim collects itrace packets (see review in the related work section) and constructs the upstream router map. During the attack, the victim uses our packet marking scheme to quickly trace back the attacker.

Finally, in the real deployment of this protocol, we can also build an exploration protocol into the routers to support incremental deployment. Thus the victim can get the map of upstream routers which implement the advanced marking protocol and the authenticated marking protocol.

B. Related Work

Researchers have proposed various schemes to address the IP traceback problem. Unfortunately they are mostly inefficient or ineffective and not robust against DDoS. Ferguson and Senie proposed ingress filtering where each router blocks packets that arrive with illegitimate source addresses [17]. This approach requires the router to have sufficient power to verify the IP address of each packet and to have sufficient knowledge to distinguish between legitimate and illegitimate addresses. Also the effectiveness of the approach depends of widespread deployment. Burch and Cheswick proposed controlled flooding [18]. In this approach, the victim floods some network selectively during the attack to check the correlation of the flooding with the attack and gather information about the sources of the attacks from the correlation. This approach is only applicable during on-going attacks, introduces large overhead and cannot deal with DDoS. Sager [19] and Stone [20] propose logging on routers. This approach has high overhead of storage and processing. All these previous work do not consider the issue of router authentication.

Bellovin [16] proposed to use ICMP messages for authenticated IP marking and is leading the IETF working group *itrace*, which explores this approach. In this scheme, an itrace router probabilistically generates an authenticated copy of a packet, adds its own IP address as well as the IP of the previous and next hop routers, and forwards the packet either to the source or destination address. The approach of using ICMP messages and our approach can be complimentary to each other. Itrace does not need an upstream router map because the IP addresses of the routers are encoded in the itrace packets. In fact, the victim can use the information in itrace packets to build an upstream router map. A disadvantage of itrace is that it requires more attacker packets due to the lower probability of generating itrace packets. Hence by using our techniques in conjunction with itrace yields the best out of both worlds: allows the victim to build the upstream router map in peace time, and use our schemes to quickly find the attacker during times of attack. The approach of using ICMP messages also has the advantage that it can capture reflector attacks if the routers also probabilistically send itrace packets to the source IP address. Our approach could potentially capture reflector attacks if the reflectors probabilistically copies the markings into replied packets.

Dean, Franklin and Stubblefield [21] propose a nice alternative marking scheme using noisy polynomial reconstruction. Their scheme does not require an upstream router map. Unfortunately their scheme is less efficient in presence of multiple attackers as the number of packets needed to reconstruct the attacking graph is quadratic to the number of attackers instead of linear in our scheme. Also because their marking scheme does not have the distance field as in FMS and our scheme, it is more vulnerable to fake markings put in the packets by the attackers. Because the marking probability has to be low enough to ensure the attack graph can be reconstructed from a reasonable number of packets, the attacker can actually put in fake markings that remain unchanged and consist of the majority of the markings received by the victim. The smart attackers can even put in fake markings according to the right probability distribution thus the victim will reconstruct a wrong attack graph.

VI. Conclusion

In this paper, we present two new schemes, the Advanced Marking Scheme and the Authenticated Marking Scheme, which allow the victim to traceback the approximate origin of spoofed IP packets. Our techniques have very low network and router overhead and support incremental deployment. In contrast to previous work, our marking techniques have significantly higher precision (lower false positive rate) and lower computation overhead for the victim to reconstruct the attack paths under large scale distributed denial-of-service attacks. Furthermore the Authenticated Marking Scheme provides efficient authentication of routers' markings such that even a compromised router cannot forge or tamper markings from other uncompromised routers.

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APPENDIX

I. ANALYZING THE LIMITATION FOR DDOS IN THE FRAGMENT MARKING SCHEME

The paper [5] mainly considers denial-of-service with a single attacker site. In this section, we analyze and illustrate that the Fragment Marking scheme (FMS) is inefficient and inaccurate under even a small scale of DDoS.

In FMS each attack packet contains the 16-bit marking block including a 5-bit *distance* field, a 3-bit *fragment ID* field, and a 8-bit *edge fragment* field. Each router's IP address is encoded using eight 11-bit fragments and each packet will probabilistically contain one of the eight fragments from the router who marked the packet. We denote the set of unique edge fragments marked with a distance d and fragment ID f as $\Psi_{d,f}$. Because for each distance d, in the eight sets $\Psi_{d,0}, \ldots, \Psi_{d,7}$, the victim cannot distinguish which eight fragments are from the encoding of the same router, in order to reconstruct the attack graph, the victim needs to consider all possible ordered combination of the eight sets $\Psi_{d,0}, \ldots, \Psi_{d,7}$ and check which combinations have the right format (by checking that the hash value of the odd bits match the even bits). We denotes the set of these combinations as C_d. Clearly, $|C_d| = \prod_{0 \le f \le 7} |\Psi_{d,f}|$. In case of DDoS, $|\Psi_{d,f}|$ could be quite high. Thus, with presence of multiple attacker sites, the Fragment Marking scheme severely suffer from the following two main problems:

- High computation overhead

Assume in the reconstructed attack graph, the number of distinct routers at distance d is $|S_d|$. Then to reconstruct the routers at distance $d+1$, the victim XORs each element x in C_{d+1} with each element y in S_d, computes $z = x \oplus y$, and checks whether z has the right format. Denote the set of the XOR results as Γ_{d+1}, the number of combinations to be checked is

$$|\Gamma_{d+1}| = |S_d| \times |C_{d+1}| = |S_d| \times \prod_{0 \le f \le 7} |\Psi_{d+1,f}|.$$

So the total number of combinations to be checked for all the distances is

$$|\Gamma| \quad = \sum_{0 \le d \le maxd} (|S_{d-1}| \times \prod_{0 \le f \le 7} |\Psi_{d,f}|),$$

using convention $|S_{-1}| = 1$. It requires at least one hash computation to check one combination. As we show in the experiments in subsection III-C, the computation overhead is considerable.

- Large number of false positives

For each such z in the set Γ, the probability that it is a valid IP encoding is $1/2^{32}$ when z is not on the attack paths, because the hash value is 32 bits. So the expected number of elements in Γ that are valid IP encoding is $|\Gamma|/2^{32}$, denoted as α. Because an IP address is 32 bits, so the expected number of false positives is

$$\mathsf{E}[\text{false positives}] = (1 - (1 - 1/2^{32})^{\alpha}) \cdot 2^{32}.$$

When $\alpha \ll 2^{32}$, $\mathsf{E}[\text{false positives}] \doteq \alpha = |\Gamma|/2^{32}$. As we show in the experiments in subsection III-C, even for a DDoS with 25 attackers, the reconstruction can result in thousands of false positives.