Mapping Internet Sensors With Probe Response Attacks

John Bethencourt Jason Franklin Mary Vernon

Computer Sciences Department
University of Wisconsin, Madison
{bethenco, jfrankli, vernon}@cs.wisc.edu

Abstract

Internet sensor networks, including honeypots and log analysis centers such as the SANS Internet Storm Center, are used as a tool to detect malicious Internet traffic. For maximum effectiveness, such networks publish public reports without disclosing sensor locations, so that the Internet community can take steps to counteract the malicious traffic. Maintaining sensor anonymity is critical because if the set of sensors is known, a malicious attacker could avoid the sensors entirely or could overwhelm the sensors with errant data.

Motivated by the growing use of Internet sensors as a tool to monitor Internet traffic, we show that networks that publicly report statistics are vulnerable to intelligent probing to determine the location of sensors. In particular, we develop a new "probe response" attack technique with a number of optimizations for locating the sensors in currently deployed Internet sensor networks and illustrate the technique for a specific case study that shows how the attack would locate the sensors of the SANS Internet Storm Center using the published data from those sensors. Simulation results show that the attack can determine the identity of the sensors in this and other sensor networks in less than a week, even under a limited adversarial model. We detail critical vulnerabilities in several current anonymization schemes and demonstrate that we can quickly and efficiently discover the sensors even in the presence of sophisticated anonymity preserving methods such as prefix-preserving permutations or Bloom filters. Finally, we consider the characteristics of an Internet sensor which make it vulnerable to probe response attacks and discuss potential countermeasures.

1 Introduction

The occurrence of widespread Internet attacks has resulted in the creation of systems for monitoring and producing statistics related to Internet traffic patterns and anomalies. Such systems include log collection and analysis centers [1, 2, 3, 4, 5], collaborative intrusion detection systems [6, 7], honeypots [8, 9], Internet sinks [10], and network telescopes [11]. The integrity of these systems is based upon the critical assumption that the IP addresses of systems that serve as sensors are secret. If the set of sensors for a particular network is discovered, the integrity of the data produced by that network is greatly diminished, as a malicious adversary can avoid the sensors or skew the statistics by poisoning the sensor's data.

Distributed Internet sensors aid in the detection of widespread Internet attacks [12, 13] which might otherwise be detectable only within the firewall and IDS logs of an individual organization or through a forensic analysis of compromised systems. In addition, systems such as Autograph [14], Honeycomb [15], and EarlyBird [16] which rely on Internet sensors to capture worm packet contents for use in the automatic generation of worm signatures would be unable to defend against worms which avoid their previously mapped monitoring points.

Of primary concern to the security community are Internet sensors that enable collaborative intrusion detection through a wide area perspective of the Internet. Such systems are in their infancy, but have been proposed in systems like DOMINO [6] and have been partially implemented in security log analysis centers like the SANS Internet Storm Center [1]. Other examples include Symantec's DeepSight [17], myNetWatchman [18], the University of Michigan Internet Motion Sensor [19, 20], CAIDA [2], and iSink [10]. In most cases, sources submit logs to a central repository which then produces statistics and in some cases provides a query interface to a database. In such systems, the probe attacks developed in this paper can compromise the anonymity of those who submit logs to the analysis center and thus enable an attacker to avoid detection. Similarly, the probe attacks developed in this paper can compromise the identity of systems that are used as honeypots that report similar kinds of attack statistics. In this case, the sensor network might still detect malicious activity from worms that probe randomly [21, 22] or due to backscatter from spoofed addresses used in denial of service attacks [23], but many new attacks could be designed to avoid detec-

Date and Time	Submitter ID	Source IP	Source Port	Dest. IP	Dest. Port
1/04/05 10:32:15	384	209.237.231.200	1956	64.15.205.183	132
1/04/05 10:30:41	1328	216.187.103.168	4659	169.229.60.105	80
1/04/05 10:30:02	1945	24.177.122.32	3728	216.187.103.169	194
1/04/05 10:28:24	879	24.168.152.10	518	209.112.228.200	1027

Table 1: Example packet filter log that might be submitted to the ISC.

tion by the sensors.

A variety of methods for maintaining the privacy of organizations submitting sensor logs to analysis centers have been proposed or are in use. The simplest method is to remove potentially sensitive fields (typically those containing IP addresses of sensor hosts within the organization) from the logs before they are transmitted to the analysis center or from the reports produced by the analysis center before they are published. This widely used method is sometimes referred to as the black marker approach. A less drastic method of anonymizing IP addresses is to truncate them, giving only the subnet or some other number of upper bits. This approach allows the resulting reports to contain more useful information while still not revealing whole addresses. It has been used in some of the CAIDA logs and in the reports of myNetWatchman. Another practice sometimes employed is hashing the sensitive data. This approach allows another person who has hashed the same information (e.g., the IP address of a potentially malicious host) to recognize the match between their anonymized logs and those of another. A more sophisticated technique for anonymizing IP addresses is the use of Bloom filters [24, 25, 7]. The Bloom filters are normally used to store sets of source IP addresses with the intention of making it difficult to enumerate the addresses within that set but easy to perform set membership tests and set unions. All of these techniques fail to prevent the probe response attacks discussed in this paper. In fact, each of these methods of obscuring a field (apart from the black marker approach, which completely omits it) leaks information useful in carrying out the attack.

Several other methods of anonymizing sensor logs have been proposed. One method is to apply a keyed hash or MAC to IP addresses. Alternatively, one may apply a random permutation to the address space (or equivalently, encrypt the IP address fields with a secret key). In particular, much attention has been given to prefix-preserving permutations [26, 27, 28], which allow more meaningful analysis to be performed on the anonymized logs. Although these techniques do in fact prevent the fields to which they are applied from being used to enable probe response attacks, the attacks are still possible if other fields are present. As will be shown in Section 6.1, nearly any useful information published by the analysis center can be used to mount an attack.

The main contributions of this paper include the introduction of a new class of attacks capable of locating Internet sensors that publicly display statistics. This gives insights into the factors which affect the success of probe response attacks. We also discuss countermeasures that protect the integrity of Internet sensors and still allow for an open approach to data sharing and analysis. Without public statistics, the benefits of a widely distributed network of sensors are not fully realized as only a small set of people can utilize the generated statistics.

The remainder of this paper is organized as follows. We discuss related work in Section 2 and the Internet Storm Center in Section 3. We give a fully detailed example of a probe response attack in Section 4. In Section 5, we describe the results of simulations of the example attack. In Section 6, we generalize the example to an entire class of probe response mapping attacks and discuss their common traits. We discuss potential countermeasures in Section 7 and conclude in Section 8.

2 Related Work

Guidelines for the design of a Cyber Center for Disease Control, a sophisticated Internet sensor network and analysis center, have been previously proposed [29]. Staniford et al. mention that the set of sensors must be either widespread or secret in order to prevent attackers from avoiding them entirely. They assess the openness with which a Cyber CDC should operate and conclude that such such a system should only make subsets of information publicly available. Their contribution includes a qualitative analysis of trade-offs but not a quantitative analysis of the nature of the threat. In this paper, we develop an algorithm that serves to delineate the precise factors that need to be considered when designing Internet analysis centers for security and privacy. In addition, we investigate how quickly the algorithm can determine sensor identities through a case study on the Internet Storm Center, as well as for more general locations of the sensor nodes. Lincoln et al. [30] prototype a privacy preserving system with live sensors and analyze the system's performance, but do not analyze mapping attacks or defenses. Gross et al. [25] describe a system which uses Bloom filters to preserve the privacy of the sensors. In Section 7.1 we describe how probe response techniques could efficiently subvert Bloom filters.

Inadequacies have been previously pointed out in the measures taken to ensure the privacy of organizations that send their logs to such analysis centers [31]. However, previous work has focused on attacks on anonymization schemes that are only possible if the attacker is capable of interacting with the network sensors. As the location of the network sensors is kept secret, it

Port	Reports	Sources	Targets
325	99321	65722	39
1025	269526	51710	47358
139	875993	42595	180544
3026	395320	35683	40808
135	3530330	155705	270303
225	8657692	366825	268953
5000	202542	36207	37689
6346	2523129	271789	2558

Table 2: Example excerpt from an ISC port report.

is not possible to carry out such attacks. Little to no attention has been given to the problem of discovering the location of the sensors. We provide techniques that accomplish this. In addition, little attention has been given to the fact that the identity of the organizations and the specific addresses they monitor must remain secret to ensure the integrity of the statistics produced by the analysis center, particularly if the statistics are meant to be employed in stemming malicious behavior. By demonstrating that it is possible to foil the current methods for maintaining the secrecy of the sensor locations, we show the importance of this issue.

For example, Pang and Paxson [32] consider the possibility of "indirect exposure" allowing attackers to discover the values of anonymized data fields by considering other parts of the available information. They do not, however, consider how or whether one might be able to map the locations of Internet sensors, a prerequisite to interacting with them. Similarly, Xu et al. [28] describe a prefix-preserving permutation based method for anonymizing IP addresses that is provably as secure as the TCPdpriv scheme [27] and consider the extent to which additional address mappings may be discovered if some are already known. They also mention active attacks in passing and point out that defense against these attacks is tricky. We develop in depth an active mapping attack that is effective even on reports that subject IP addresses to prefix-preserving permutations and further discuss countermeasures.

3 Background: the Internet Storm Center

3.1 Overview

The Internet Storm Center of the SANS Institute is one of the most important existing examples of systems which collect data from Internet sensors and publish public reports. Furthermore, it is a challenging network to map, as will be shown in Section 5.5, due to its large number of sensors with non-contiguous IP addresses. Thus, in order to demonstrate the possibility of mapping sensors with probe response attacks in general, we describe and evaluate the algorithm initially using the ISC and then generalize the algorithm and simulation results to other sensor networks. In this way, the ISC serves as a case study in the feasibility of mapping sensor locations.

The ISC collects firewall and IDS logs from approximately 2,000 organizations, ranging from individuals to universities and corporations [33]. This collection takes place through the ISC's DShield project [34]. The ISC analyzes and aggregates this information and automatically publishes several types of reports which can be retrieved from the ISC website. These reports are useful for detecting new worms and blacklisting hosts controlled by malicious users, among other things. Currently, the logs submitted through the DShield project are almost entirely packet filter logs listing failed connection attempts. They are normally submitted to the ISC database automatically by client programs running on the participating hosts, typically once per hour. The logs submitted are of the form depicted in Table 1. These logs are used to produce the reports published by the ISC, including the top ten destination ports and source IP addresses in the past day, a "port report" for each destination port, a "subnet report," autonomous system reports, and country reports.

3.2 Port Reports

In general, many types of information collected by Internet sensors and published in reports may be used to conduct probe response attacks, as will be discussed in Section 6. For our case study using the ISC, we will primarily concern ourselves with the ISC's port reports, as these are representative of the type of statistics that other Internet sensor networks may provide and are general in nature. A fictional excerpt of a port report is given in Table 2. A full listing all of the 2^{16} possible destination ports that had any activity in a particular day may be obtained from the ISC website. For each port, the report gives three statistics, the number of (unfortunately named) "reports," the number of sources, and the number of targets. The number of sources is the number of distinct source IP addresses appearing among the log entries with the given destination port; similarly, the number of targets is the number of distinct destination IP addresses. The number of "reports" is the total number of log entries with that destination port (generally, one for each packet). Although the port reports are presented by day and numbers in the port report reflect the totals for that day, the port reports are updated more frequently than daily. One may gain the effect of receiving a port report for a more fine-grained time interval by periodically requesting the port report for the current day and subtracting off the values last seen in its fields.

4 Example Attack

We now present a detailed algorithm which uses a straightforward divide and conquer strategy along with some less obvious practical improvements to map the sensor locations using information found in the ISC port reports. In Section 6 we outline how the algorithm could be applied to map the sensors in other networks (including Symantec DeepSight and myNetWatchman) using information in those sensor network reports.

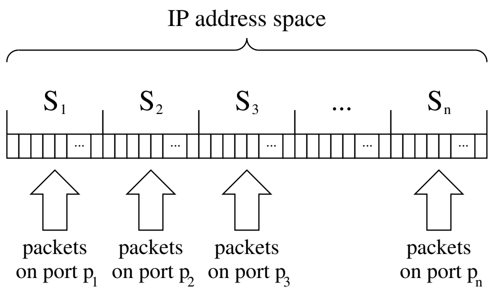


Figure 1: The first stage of the attack.

4.1 Introduction to the Attack

The core idea of the attack is to probe an IP address with activity that will be reported to the ISC if the addresses are among those monitored, then check the reports published by the network to see if the activity is reported. If the activity is reported, the host probed is submitting logs to the ISC. Since the majority of the reports indicate an attempt to make a TCP connection to a blocked port (which is assumed to be part of a search for a vulnerable service), a single TCP packet will be detected as malicious activity by the sensor.[1] To distinguish our probe from other activity on that port, we need to send enough packets to significantly increase the activity reported. As it turns out, a number of ports normally have little activity, so this is not burdensome. This issue will be further discussed in Section 4.3. This probing procedure is then used for every possible IP address. It is quite possible to send several TCP/IP packets to every address; the practical issues relating to such a task are considered in Section 5.

The simplest way to find all hosts submitting logs to the ISC is then to send packets to the first IP address, check the reports to determine if that address is monitored, send packets to the second IP address, check the reports again, and so on. However, some time must be allowed between sending the packets and checking the reports. Participants in the ISC network typically submit logs every hour, and additional time should be allowed in case some participants take a little longer, perhaps for a total wait of two hours. Obviously, at this rate it will take far too long to check every IP address one by one.

In order for a sensor probing attack to be feasible, we need to test many addresses at the same time. Two observations will help us accomplish this. First, the vast majority of IP addresses either do not correspond to any host, or correspond to one that is not submitting logs. With relatively few monitored addresses, there will necessarily be large gaps of unmonitored address space. Hence, we may be able to rule out large numbers of addresses at a time by sending packets to each, then checking if any activity is reported at all. If no activity is reported, none of the addresses are monitored. Sending packets to blocks of addresses numerically adjacent is likely to be especially effective, since monitored addresses are likely to be clustered to some extent, leaving gaps of addresses that may be ruled out. Second, since malicious activity is reported by port, we can use different ports to conduct a number of tests simultaneously. These considerations led the authors to the method described in the following section. It is worth noting that the problem solved by this algorithm is very similar to the problems of group blood testing [35]. However, much of theoretical results from this area focus on optimizing the solutions in a different way than we would like to and thus are not directly applicable to this problem.

4.2 Basic Probe Response Algorithm

First Stage

We begin with $0, 1, 2, \ldots 2^{32} - 1$ as our (ordered) list of IP addresses to check. As a preprocessing step, we filter out all invalid, unroutable, or "bogon" addresses [36]. Approximately 2.1 billion addresses remain in the list. Suppose n ports $p_1, p_2, \ldots p_n$ can be used in conducting probes. To simplify the description of the basic algorithm, we assume in this section that these ports do not have any other attack activity; we relax this restriction in Section 4.3. In the first stage of the attack, we divide the list of addresses into n intervals, $S_1, S_2, \ldots S_n$. For $i \in \{1, \ldots n\}$, we send a SYN packet[2] on port p_i to each address in S_i, as depicted in Figure 1. We then wait two hours and retrieve a port report for each of the ports. Note that we now know the number of monitored addresses in each of the intervals, since the reports tell not only whether activity occurred, but also give the number of targets. All intervals lacking any activity may be discarded; the remaining intervals are passed to the second stage of the attack along with the number of monitored addresses in each.

Second Stage

The second stage of the attack repeats until the attack is complete. In each iteration, we take the k intervals that currently remain, call them $R_1, \ldots R_k$, and distribute our n ports among them, assigning $\frac{n}{k}$ to each.[3] Then for each $i \in \{1, \ldots k\}$, we do the following. Divide R_i into $\frac{n}{k} + 1$ subintervals, as shown in Figure 2. We send a packet on the first port assigned to this interval to each address in the first subinterval, a packet on the second port to each address in the second subinterval, and so on, finally sending a packet on the last port to each address in the $\frac{n}{k}$th subinterval, which is the next to last. We do not send anything to the addresses in the last subinterval. We will instead deduce the number of monitored addresses in that subinterval from the number of monitored addresses in the other subintervals. After this process is completed for each of the subintervals of each of the remaining intervals, we wait two hours and retrieve a report. Now we are given the number of monitored addresses in each of

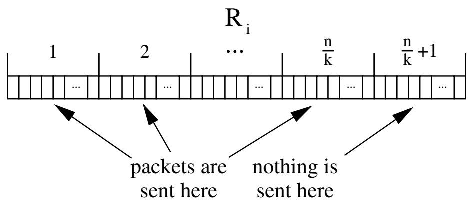


Figure 2: Subdividing an interval R_i within the second stage of the attack.

the subintervals except the last in each interval. We then determine the number in the last subinterval of each interval by subtracting the number found in the other subintervals from the total known to be in that interval. At this point, empty subintervals may again be discarded. Additionally, subintervals with a number of monitored addresses equal to the number of address in the subinterval may be discarded after adding their addresses to a list of monitored addresses found so far. The remaining subintervals, which contain both monitored addresses and unmonitored addresses, may now be considered our new set of remaining intervals $R'_1, \ldots R'_{k'}$, and we repeat the procedure.

By continuing to subdivide intervals until each is broken into pieces full of monitored addresses or without any monitored addresses, we eventually check every IP address and produce a list of all that are monitored. This process may be visualized as in Figure 3, which gives an example of the algorithm being applied to a small number of addresses. The first row of boxes in the figure represent the initial list of IP addresses to be checked, with monitored addresses shaded. Six ports are used to probe these addresses, giving the numbers of monitored addresses above the row. Three intervals are ruled out as being empty, and the other three are passed to the second stage of the algorithm. The six ports are used in the first iteration of the second stage to eliminate three subregions (of two addresses each), and mark one subregion as filled with monitored addresses. The second iteration of the second stage of the algorithm terminates, having marked all addresses as either monitored or unmonitored. One caveat of the algorithm that did not arise in this example is that the number of remaining intervals at some stage may exceed n, the number of available ports. In this case it is not possible to divide all those intervals into subintervals in one time period, since at least one port is needed to probe each interval. When this cases arises, we simply select n of the subintervals to probe, and save the other subintervals for the next iteration.

4.3 Dealing With Noise

We now turn to a practical problem that must be addressed if the attack is to function correctly. The problem is that sources other than the attacker may also be sending packets to monitored addresses with the same destination ports that the algorithm is using, inflating the number of targets reported. This can cause the algorithm to produce both false positives and false negatives. This background activity may be considered noise that obscures the signal the attacker needs to read from the port reports. For a large number of ports, however, this noise is typically quite low, as shown by Table 3. Each row in the table gives the approximate number of ports that typically have less than the given number of reports. The numbers were produced by recording which ports had less than the given number of reports every day over a period of ten consecutive days.

ports	reports
561	≤ 5
$19,364$	≤ 10
$41,357$	≤ 15
$51,959$	≤ 20
$56,305$	≤ 25

Table 3: Ports with little activity.

A simple technique allows the algorithm to tolerate a certain amount of noise at the expense of sending more packets. If there are normally, say, less than five reports for a given port p, we may use port p to perform probes in our algorithm by sending five packets whenever we would have otherwise sent one. Then when reviewing the published port report, we simply divide the number of reports by five and round down to the nearest integer to obtain the actual number of submitting hosts we hit. We subsequently refer to this practice as using a "report noise cancellation factor" of five. Thus by sending five times as many packets, we may ensure that the algorithm will function correctly if the noise on that port is less than five reports. Similarly, by using a report noise cancellation factor of ten, we may ensure the algorithm operates correctly when the noise is less than ten reports. By examining past port reports, we may determine the least active ports and the number of packets necessary to obtain accurate results when using them to perform probes.

4.4 Improvements

False Positives and Negatives

The attack may potentially be sped up by allowing some errors to occur. If it is acceptable to the attacker to merely find some superset of (i.e., a set containing) the set of hosts submitting their logs to the ISC, they may simply alter the termination conditions in the algorithm. Rather than continuing to subdivide intervals until they are determined to consist entirely of either monitored or unmonitored addresses, the attacker may mark all addresses in an interval as monitored and discontinue work on the interval when it is determined to consist of at least, say, 10 percent monitored addresses. In this way, when the algorithm completes, at most 90 percent of addresses determined to be monitored are false positives. Even though that is a large amount of error, the vast majority of the addresses on the Internet would remain available for the attacker to attempt to compromise, free from the fear of being detected by the ISC. Alternatively, if the attacker is willing to accept some false negatives (i.e., find a sub-

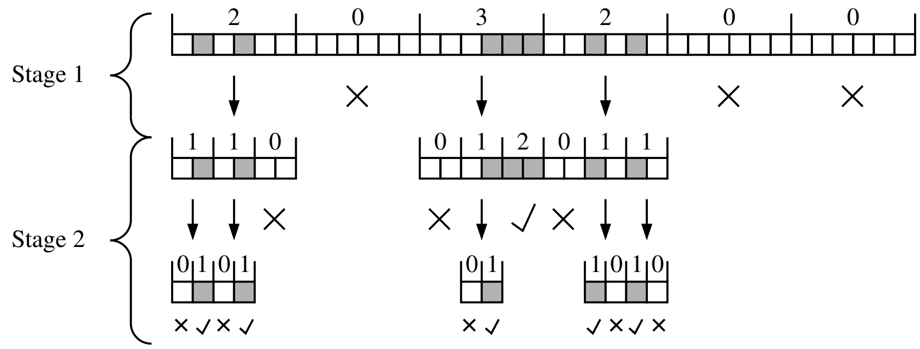


Figure 3: Illustration of the sensor probing algorithm.

set of the hosts participating in the network), they may discard an interval if the fraction of the addresses that are monitored within it is less than a certain threshold, again speeding up the attack. In Section 5 we provide quantitative results on the speedup provided by these techniques in the case of mapping the ISC.

Using Multiple Source Addresses

Speed improvements may also be obtained by taking advantage of the sources field of the port reports. By spoofing source IP addresses while sending out probes, an attacker may encode additional information discernible in this field. If in the course of probing an interval of addresses with a single port, the attacker sends multiple packets to each address from various numbers of source IP addresses and takes note of the number of sources reported, they may learn something about the distribution of monitored addresses within the interval in addition to the number of monitored addresses. The following is a method for accomplishing this.

Multiple Source Technique Before probing an interval of addresses on some port, we further divide the interval into some number of pieces k, hereafter referred to as the "multiple source factor." To the addresses in the first piece, we send packets from a single source. To each of the addresses in the second piece, we send packets from two sources. For the third piece, we send packets from four source addresses to each address. In general, we send packets from 2^{i-1} source addresses to each address in the ith piece. Note that we already are sending multiple packets to each address in order to deal with the noise described in Section 4.3. If 2^{k-1} is less than or equal to the report noise cancellation factor, then we can employ this technique without sending any more packets; otherwise, more bandwidth is required to send all 2^{k-1} packets to each address.

When the port report is received, we may determine whether any of the pieces lacked monitored addresses by considering the number of sources reported. For example, suppose $k = 3$ (i.e., we divide our interval into three pieces) and five sources are reported. Then we know that there are monitored addresses in the first and third intervals, and that there are no monitored addresses in the second interval. This additional information increases the efficiency of the probing algorithm by often reducing the size of the intervals that need to be considered in the next iteration, at the expense of potentially increasing the bandwidth usage. Of course, this technique is only useful to a limited degree, due to the exponential increase in the number of packets necessary to use it more extensively. Depending on the level of noise on the port, using a multiple source factor of two or three achieves an improvement in probing efficiency with little to no increase in the bandwidth requirements.

Noise In order for this technique to perform accurately, we must deal with noise appearing in the sources field of the port reports in addition to the reports field. If even a single source address other than those spoofed by the attacker is counted in the reported number of sources, the attacker will have a completely inaccurate picture of which pieces are empty. This problem may be solved in a manner similar to the method for tolerating noise in the number of reports. Rather than sending sets of packets with $1, 2, 4, \ldots$ and 2^{k-1} different source addresses to the k pieces, we may use $1m, 2m, 4m, \ldots$ and $2^{k-1}m$ sources, where m is a positive integer hereafter referred to as the "source noise cancellation factor." Then the reported number of sources may be divided by m and rounded down, ensuring accurate results if the noise in the number of sources was less than m. For example, if a particular port normally has less than three sources reported (when the attacker is not carrying out their attack) and the attacker is dividing each interval into four pieces, they may send sets of packets with $3, 6, 12$, and 24 sources. If seventeen sources are then reported, they divide by three and round down to obtain five, the sum of one and four. The attacker may then conclude that the second and fourth intervals have no monitored addresses, and that the first and third intervals do have monitored addresses.

Egress Filtering There is another practical concern relating to this technique, and that is egress filtering of IP packets with spoofed sources. The careful attacker should be able to avoid running into any problems with this by selecting source addresses similar to actual ones that are then likely to be valid addresses within the same network. Not many such addresses are needed (since this technique will likely only be employed to a limited degree for the aforementioned reasons of bandwidth), and it is a simple task to verify whether packets with a given spoofed address will be filtered before leaving the network. All that is necessary is to send one to an available machine outside the network and see if it arrives.

5 Simulation of the Attack

In the following section we describe the results of several simulated probe response attacks on the ISC, assuming the set of ISC sensor locations as well as various other possible sets of sensor locations. For each attack, we detail the results including the time required and the number of packets sent, along with a description of how the attack progresses under various levels of resources and with optimizations to our algorithm.

In the first scenario, we determine the exact set of monitored addresses. While this attack is the most accurate, it is also the most time consuming. Depending on the intentions of the attacker (see Section 5.6), it may not be necessary to find the exact set of monitored addresses. Thus, we also simulate finding a superset and a subset of the monitored addresses. These scenarios may be more practically useful since they require less time and resources.

In each case, we examine the interaction between the accuracy, time, and resources necessary to undertake our attack. We demonstrate that the proposed attack is feasible with limited resources and under time constraints, and discuss the impact on the integrity of the sensor network reports. Since an attacker can obtain an accurate map of the sensors in less than a week, the integrity of the sensor network reports is at risk. Section 6 discusses how to apply the algorithm using reports from other sensor networks, and Section 7 discusses possible countermeasures that sensor networks can use to improve their vulnerability to such attacks.

5.1 Adversarial Models

Available Bandwidth

In order to examine a broad range of scenarios, we provide the results of simulations under three distinct adversarial models, the primary difference between models being the resources of the attacker. Our first attacker has 1.544 Mbps of upload bandwidth, equivalent to a T1 line and hereafter will be referred to as the T1 attacker. Our second attacker has significantly more upload bandwidth, 38.4 Mbps, and hereafter will be referred to as the fractional T3 attacker or, for brevity, the T3 attacker. Finally, we examine the rate at which an attacker with 384 Mbps of bandwidth could complete our attack. This adversary will be referred to as the OC6 attacker.

While each attacker is denoted by a specific Internet connection, our algorithm is not dependent upon a particular Internet connection or attacker configuration. Our algorithm can be executed on a distributed collection of machines or a single machine, with the time required to complete our attack dependent only on the aggregate upload bandwidth. Neither the number of machines nor their specific configurations are important as long as they can be coordinated to act in unison. In addition, because our attack does not require a response to be received from a probe or any significant amount of state to be maintained, we can ignore download bandwidth, network latency, and computing resources.

Botnets

One potential way to acquire the necessary bandwidth is to use a “botnet,” or collection of compromised machines acting in unison. The technology required to coordinate such a collection of machines for a probe response attack is currently available and is under some estimations commonly used. The most ubiquitous families of botnet software are reported to be Gaobot, Randex, and Spybot. The required upload bandwidth for the T1 attacker could easily be achieved by a dozen cable modems, a very small botnet. Similarly, the upload bandwidth for the fractional T3 attacker and the OC6 attacker could be achieved by using around 250 and 2,500 cable modems, respectively. Botnets of these scales are not uncommon [37].

It should be noted that the bandwidth required for the swift completion of the attack varies widely based upon the noise cancellation factors and the multiple source factor. In all of our attack scenarios, we have configured the parameters of our algorithm to best match the resources of the attacker, resulting in a near optimal outcome for each attacker. Since the only factors that affect the time required for our attack to complete are the upload bandwidth and parameters to the algorithm, it is reasonably easy to find a near optimal set of parameters for any given bandwidth. In addition, the number of ports that have sufficiently low noise to be used in our attack can easily be calculated from past port reports and is found to remain steady throughout the duration of the attack.

Variation in Performance

Each of our attackers is representative of a class of adversaries ranging from the most basic attacker with a dozen machines to a sophisticated and resourceful group with thousands of machines at their command. Using these classes of attackers, we show the tradeoffs between accuracy, time, and resources while providing concrete results including the time required to complete the attack and the rate at which the attack progresses.

What may not be immediately obvious is the fact that almost any level of resources is sufficient to map the addresses monitored by a log collection and analysis center in a few months. For instance, while not a likely case, an attacker equipped only with a DSL line could find the exact set of addresses monitored by the ISC in under four months. Log collection projects with fewer participants than the ISC could be mapped in even less time.

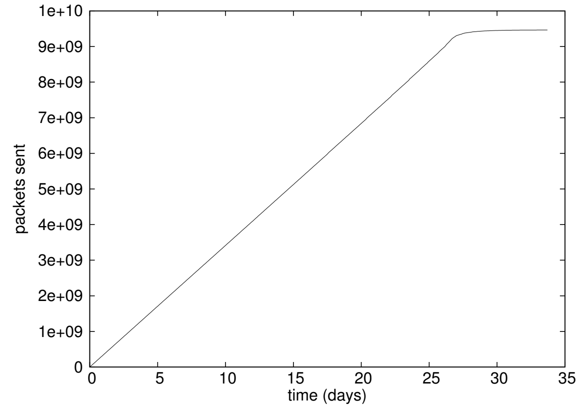
5.2 Finding the Set of Monitored Addresses

First, we detail the results of our simulation of the fully accurate attack, which finds the exact set of monitored addresses. Two useful statistics that will help us to explain the specifics of an attack are the number of probes sent and the fraction of monitored addresses known at a particular time. We explain the significance of each of these statistics and then use them to highlight similarities and differences in the simulations under different adversarial models.

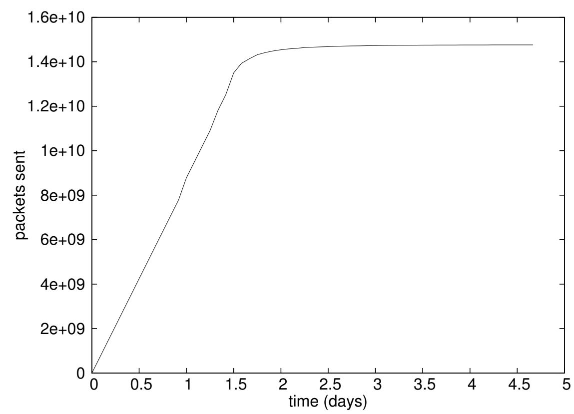
Number of Probes Sent

As previously explained in Section 4.2, our attack utilizes repeated probing of IP addresses with SYN packets. Since we must probe approximately 2.1 billion addresses with at least one packet each, the number of packets sent by an attack is significant. While the specifics vary based on the optimizations used, when finding the exact set of monitored addresses, our algorithm may send from nine billion to twenty seven billion SYN packets over a several day to several week period. As a result of this hefty requirement, our three attackers, with their widely different upload bandwidths, are able to complete the attack in widely differing times. For instance, the time required to find the set of monitored addresses exactly ranges from around 3 days for the OC6 attacker to approximately 34 days for the T1 attacker. While the time required to complete an attack is not directly proportional to the number of probes sent, as upload bandwidth increases, the time required to complete an attack monotonically decreases.

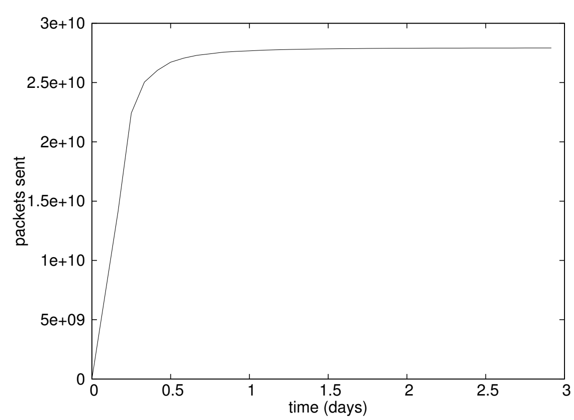
Figure 4 shows the specific number of packets sent per attacker and the rate at which packets are sent when finding the exact set of monitored addresses. The bend in the curve represents the point at which the attacker's bandwidth is sufficient to send all the packets required for a particular two hour interval within the same two hour interval. Before the bend, the attacker's progress is limited by the rate at which they can send out packets. This period generally corresponds to the first stage of the attack, that is, the initial probing of the entire non-bogon address space. The bandwidth used in this stage accounts for the majority of the total bandwidth used, as large portions of the address space are ruled out in this first pass. After the bend, the attacker's progress is limited by the two hour wait between sending a set of probes and checking the corresponding port reports. This situation is generally the case throughout most of the iterations of the second stage of the algorithm. For the remainder of our analysis, we will focus on the second statistic, the fraction of monitored addresses known at a particular time.



(a) Packets sent by T1 adversary.

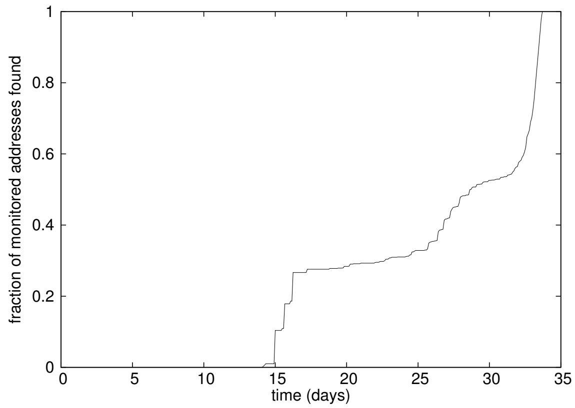


(b) Packets sent by fractional T3 adversary.

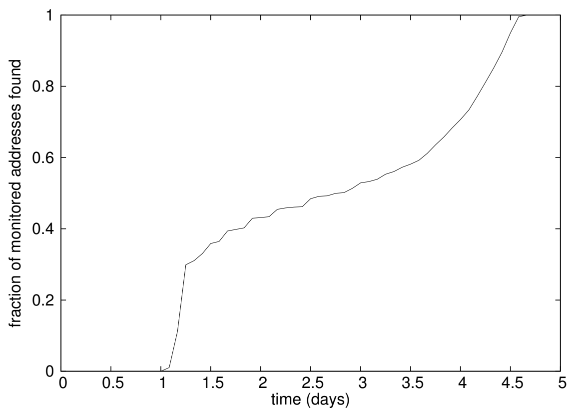


(c) Packets sent by OC6 adversary.

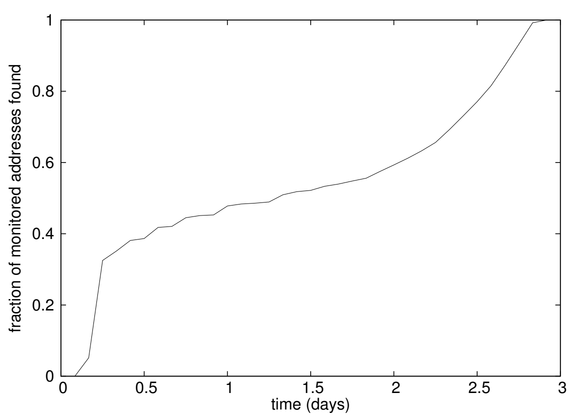
Figure 4: Number of packets sent for each attack simulation.



(a) T1 adversary progress.



(b) T3 adversary progress.



(c) OC6 adversary progress.

Figure 5: The attacker's progress in discovering monitored addresses.

Attack Progress

Figure 5 shows the fraction of monitored addresses that are known throughout the execution of the attack for each of our three specific simulations. While in each case the end result is always the same, the time required and the rate at which addresses are discovered, a statistic we call the attack progress, varies widely. One may notice that the lines in Figure 5 are similar in shape. This is a result of similarities in the sizes of intervals used in the algorithm and the particular distribution of monitored addresses in IP address space. Discussion of this distribution of addresses appears in Section 5.5. We will continue to use the attack progress statistic throughout our analysis as a way to provide insight into the specifics of our algorithm.

T1 Attacker Analysis

When bandwidth is highly limited as in the case of the T1 attacker, the number of packets sent in the first stage of the attack and the first several iterations of the second stage are the primary time constraint. As a result, it makes sense to reduce the number of packets sent by using ports with less noise and avoiding the use of the multiple source technique. This in turn allows an attacker to use a lower report noise cancellation factor, however this also results in fewer available ports. We have found that when one doubles the number of ports available for use by the attacker, they in turn reduce the number of intervals required to complete the attack by a factor of two. However, this is only beneficial when the attacker is able to send the number of packets required in each interval. Since this is not always possible in the case of low bandwidth attackers, it makes sense to reduce the number of packets required and in turn use fewer ports for the attack. Specific details for a near optimal set of parameters for the T1 attacker and other low bandwidth attackers follow.

When simulating our algorithm with an upload bandwidth equivalent to that of a T1, we determined that a report noise cancellation factor of two and avoiding the use of the multiple source technique was one of the best options. As a result of the T1 attacker's inability to send a sufficient amount of packets in the first stage of the algorithm and the majority of the iterations of the second stage, the T1 attack takes significantly more time to run than the T3 attack or OC6 attack. A T1 line can only send roughly 28 million SYN packets in a two hour interval, thus the T1 attacker requires several days to run the first stage of the attack. Similar results follow for most of the iterations of the second stage of the attack. This slow progress results in the complete lack of monitored addresses found within the first 15 days of the attack. However, after the T1 attacker is able to send the number of probes required for a particular interval, which happens around day 27, the remaining 60 percent of monitored addresses are found in only 7 days. In the end, the

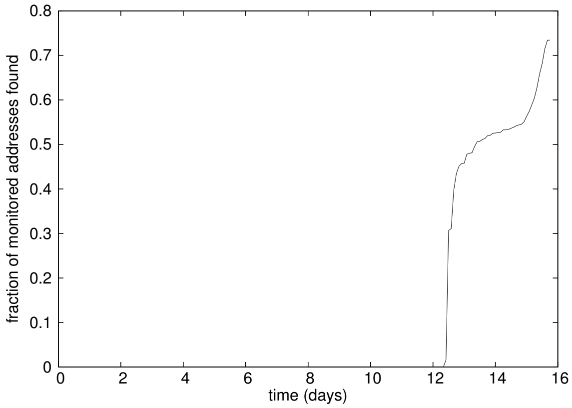


Figure 6: The T1 adversary finding a subset of the monitored addresses.

T1 attacker requires 33 days and 17 hours and the transmission of approximately 9.5 billion packets to find the exact set of monitored addresses by the ISC.

T3 Attacker Analysis

As can be seen from Figure 4(b), the T3 attacker is able to quickly send the number of probes required by the first stage of the attack and the following iterations of the second stage. With a maximum upload throughput of about 626 million SYN packets in a two hour period, the T3 attacker can complete the first stage of the attack in 23 hours. Since the first stage of the attack requires over 8 billion packets, the T3 attacker has already sent the majority of the 14 billion packets required for the entire attack and is well ahead of where the T1 attacker was at the same time.

By the end of the 30th hour, the T3 attacker has already found about 30 percent of the monitored addresses and is able to send the number of probes required by all successive intervals within the interval itself. Correspondingly, the remaining 65 percent of monitored addresses are found in the following three days. These results were achieved with a report noise cancellation factor of two, a multiple source factor of two, and a source noise cancellation factor of two. The time required for the completion of this simulated attack was 4 days and 16 hours. This represents greater than a factor of 7 reduction from the T1 attacker's 33 days and 17 hours, however this was obtained with an almost 2,500 percent increase in bandwidth.

OC6 Attacker Analysis

While the OC6 attacker has sufficient upload bandwidth to undertake a faster attack than both other adversaries, the difference between the time required for the T3 adversary and the OC6 adversary is only a fraction of the difference between the T1 and T3 adversaries. Even though the OC6 attacker has 10 times the bandwidth of the T3 attacker, an increase in the multiple source factor (the only remaining optimization possible) is not feasible because of the corresponding exponential increase in the number of probes required. We determined that a near optimal set of parameters for the OC6 attacker was a multiple source factor of two with a source based noise cancellation factor of four and a report noise cancellation factor of eight. This not only balances the number of packets required by the multiple source technique with the number required by the report noise cancellation factor, but also allows for 25 percent more ports to be used for the OC6 attack than were used for the T3 attack.

Under these parameters, the OC6 attacker can find the exact set of monitored addresses to the ISC in 70 hours. If we were to continue considering increasing bandwidths, we would continue to notice diminishing marginal returns. This is a result of the fact that the only remaining optimization possible is the usage of the multiple source technique, and, as previously stated, this results in an exponential increase in the number of packets sent while only reducing the time required to complete our attack by a few hours.[4]

5.3 Finding a Superset

By setting a configurable threshold in our algorithm (see Section 4.4), an attacker is capable of accepting some number of false positives, while avoiding false negatives. As a result, an attacker that is interested in simply avoiding detection may further improve upon the results given above by finding a superset of the monitored addresses. We detail the results of such an attack with the T3 adversarial model.

In order to compare with previous results, we use the same parameters as were used when the T3 adversary found the exact set of monitored addresses, except in this case, we specify a maximum percentage of false positives to allow on a per interval basis. With a maximum false positive rate of .94 (i.e., the number of possible false positives over the total number of IP addresses), a report noise cancellation factor of four, a multiple source factor of two, and a source noise cancellation factor of two, we are able to reduce the runtime of our attack from 112 hours to 78 hours. However, this reduction in time requires us to accept around 3.5 million false positives along with our set of monitored addresses. Allowing these false positives had little effect on the number of probes. It was reduced by less than one percent. This phenomena occurs because the final iterations of the second stage of the algorithm require fewer and fewer packets to probe the small intervals that remain. This fact can also be seen in Figure 4, where the lines flatten out near the end of the attack. Although the modest improvement in time in this case is likely not worth the decrease in accuracy, in other cases of probe response mapping attacks accepting false positives may be more useful.

type of mapping	bandwidth available	data sent	false positives	false negatives	correctly mapped addresses	time to map
exact	OC6	1,300GB	0	0	687,340	2 days, 22 hours
exact	T3	687GB	0	0	687,340	4 days, 16 hours
exact	T1	440GB	0	0	687,340	33 days, 17 hours
superset	T3	683GB	3,461,718	0	687,340	3 days, 6 hours
subset	T1	206GB	0	182,705	504,635	15 days, 18 hours

Table 4: Time to map sensor locations. (ISC sensor distribution)

5.4 Finding a Subset

Having examined the cases of finding an exact set and finding a superset, we now examine a situation where an attacker may be interested in finding a subset of the monitored addresses. While an attacker with a T3 or OC6 may attempt to find the exact set of monitored addresses, an impatient attacker or an attacker with less resources, such as the T1 attacker, may be content with finding a subset of the monitored addresses in a reduced amount of time. By allowing false negatives, an attacker may reduce the time and bandwidth necessary to undertake the attack, but still discover a large number of monitored IP addresses. An attacker who is interested in flooding the monitored addresses with spurious activity rather than avoiding them may be especially interested in allowing false negatives. In addition to saving time, an attacker finding a subset may potentially avoid detection of their attack by sending significantly fewer probes overall.

Since the difference between the time required to find the exact set of monitored addresses and the time required to find a subset of monitored addresses is less pronounced at high bandwidths, we only detail the results of finding a subset with the T1 adversary. Once again we use the same parameters that were used when the T1 adversary found the exact set of monitored addresses, except this time we set the maximum false negative rate (i.e., the number of possible false negatives over the total number of IP addresses). With a report noise cancellation factor of two, a single source address, and a maximum false negative rate of .001, we are able to reduce the runtime of our attack from 33 days and 17 hours to 15 days and 18 hours. In addition, we reduce the number of probes sent from around 9.5 billion to 4.4 billion, a reduction of over 50 percent. However, these reductions come at the cost of missing 26 percent of the sensors. The progress of this scenario is depicted in Figure 6.

5.5 General Sets of Monitored Addresses

The preceding scenarios (summarized in Table 4) demonstrate that a probe response attack is practical for mapping the IP addresses monitored by the ISC. They do not, however, reveal how dependent the running time of the attack is on this particular set of addresses. A key factor that determines the difficulty of mapping the addresses of a sensor network is the extent to which the sensors are clustered together in the space of IP addresses. As mentioned in Section 4.1, the more the addresses are clustered together, the more quickly they may be mapped. This fact is easily seen in Figure 3.

To determine how well the algorithm works more generally against various possible sets of sensor IP addresses, we generated random sets of IP addresses based on a model of the clustering. More specifically, the sizes of "clusters," or sets of sequential sensor addresses, were drawn from a Pareto distribution,[5] and the sizes of the gaps in address space between them were drawn from an exponential distribution. With the parameters of the two distributions set to fit the actual addresses of the ISC, the times to map various random sets of IP addresses are similar to the times reported in Table 4. By varying the parameters of the distributions, sets of IP addresses with various average cluster sizes were produced while holding the total number of sensors roughly constant at 680,000, the approximate number in the ISC set. For average cluster sizes of 10 or more, the attack typically takes just over two days to complete under the T3 attacker model previously described (compared to the 4 days, 16 hours to complete the attack for the actual ISC). For smaller average cluster sizes, the running time increases. Below the average cluster size of the ISC (~ 1.9), typical running times increase rapidly, with about eight days (about twice the time to map the ISC sensors) at average clusters size of about 1.6. Note that smaller sensor networks are faster to map; the ISC network is among the most challenging networks to map due to its large number of sensors with widely scattered IP addresses.

As an extreme case, a number of simulations were also run on sets of IP addresses that possessed no special clustering, again using the T3 attacker model. Specifically, the sets were produced by picking one IP address after another, always picking each of the remaining ones with equal probability. This can be considered a worst case scenario, since any real life sensor network is likely to display some degree of clustering in its set of addresses. The attack remained quite feasible in this case, taking between two to three times as long as in the ISC case when working on a set of addresses of the same size. This scenario was tested for sets of IP addresses of various sizes. The running time ranged linearly from about 3 days to map 100,000 addresses to about 21 days to map 2,000,000.

5.6 Summary and Consequences

Perhaps the most interesting results of the simulations using the addresses monitored by the ISC presented in Table 4 are the cases of discovering the exact set of monitored addresses in about a month with low bandwidth and in about three days with high bandwidth. The consequences of a malicious user successfully mapping a set of sensors are severe. Armed with a list of the IP addresses monitored by a log collection and analysis center, an attacker could avoid the monitored addresses in any future suspicious activities (such as port scanning). It would even be possible to include the list in any worms they released,[6] allowing the worms to avoid scanning any monitored addresses as they spread. Such attacks would go undetected (at least by the analysis center in question). Since organizations such as the ISC are often the first to discover the spread of new worms, a worm avoiding the addresses they monitor may go undetected for a long time. Another technique an attacker armed with a list of monitored addresses might employ is to flood monitored addresses with activity, causing valid alerts to be lost in the noise.

The most important thing to realize when considering the consequences of an adversary having obtained a list of monitored addresses is that the damage done to the distributed monitoring effort is essentially permanent. If the list were publicly released, future alerts arising from those monitored addresses could not be considered an accurate picture of the malicious activities occurring within the Internet. Since organizations cannot easily change the IP addresses available to them, and since distributed monitoring projects cannot arbitrarily select who will participate, accumulating a new set of secretly monitored IP addresses could be an extremely time consuming task.

6 Generalizing the Attack

We return now to the fact that our example algorithm for mapping a set of sensors is highly tailored to our example, the ISC, and its port reports. It is certainly conceivable that some change may be made to the way this information is reported that will confound the algorithm as it is given. But given such a change, how may we be sure that all attacks similar to the one given may be prevented? To address this problem, we need to understand what essentially allows the example attack to work.

6.1 Covert Channels in Reports

By sending probes with different destination ports to different IP addresses and considering which ports have activity reported, the attacker is able to gain some information about the set of IP addresses that could have possibly received the probes. In this way, the destination port appearing in a packet sent out and later in the port reports is used by the attacker as a covert channel [38] in a message to themselves. The covert channel stores partial information about the IP address to which the probe was directed. Similarly, (and here we are considering the "probe" to be all the packets sent to a particular address in a single round of the second stage of the algorithm) we see that the number of packets sent and the number of distinct source IP addresses they contain are covert channels that may be used to store additional information.

Viewed in this light, it is clear that many possible fields of information one may imagine appearing in the reports published by a sensor analysis center are suitable for use as covert channels in probe response attacks. Characteristics of attacks or probes that may be reported include the following.

- Time / date
- Source IP
- Source network
- Source port
- Destination network[7]
- Destination port
- Protocol (TCP or UDP)
- Packet length
- Captured payload data or signature

Our case study attack uses the time a probe was sent out, its destination port, and its set of source IP addresses as the covert channels. The possibility of characteristics of packets being used as a covert channel has been previously mentioned by Xu, et al. [28].

6.2 Other Internet Sensor Networks

To demonstrate the generality of our algorithm, we outline how an attacker could map the Symantec DeepSight Analyzer and the myNetWatchman sensor network. Table 5 summarizes the essential mapping information for Symantec DeepSight, myNetWatchman, ISC, and the modeled ISC distribution.

Symantec DeepSight

Besides the SANS Internet Storm Center, the largest Internet sensor network that publicly displays statistics is Symantec's DeepSight network. Designed much like the ISC, DeepSight provides a sensor client called the DeepSight Extractor which, once installed, forwards firewall and IDS logs from a monitored address to a central log analysis center named the DeepSight Analyzer. The DeepSight Analyzer then produces summaries and statistics related to the specific security events seen by the particular client. After installing the client software, a particular client can log into the DeepSight system and view statistics concerning the attacks seen in their own logs. This differentiates the reports of the DeepSight system from those of the ISC since the DeepSight system does not provide a global report of the activity sensed by all clients, but rather primarily a view of the events seen by a specific client.

Despite the fact that DeepSight primarily provides information concerning security events seen in a particular client's logs, they are still vulnerable to a probe response attack. In order to see how an attacker would map the DeepSight network, we first need to analyze the output provided by DeepSight. DeepSight provides each client with a detailed report of the attacks seen in their logs including the time and date, source IP address, source port, destination port, and the number of other clients affected by a particular attack. Each report listed contains roughly forty-two to seventy-four bits usable to the attacker as a covert channel. There are about ten in the time field, sixteen in each port field, and zero to thirty-two in the source address field (depending on whether the attacker needs to worry about egress filtering when spoofing source addresses and to what extent if so). With this information, an attacker could map DeepSight with a few simple modifications to our algorithm.

First, instead of using strictly the time, destination port, and set of source IP addresses to encode the destination address as in the ISC example, an attacker could encode the destination address in the source IP, destination port, source port, and time fields. Since the source IP address alone provides sufficient space to encode the destination IP address, encoding information in the source and destination ports and time field is not strictly necessary but could be useful for noise reduction purposes or if egress filtering is an issue. Second, for each unique combination of fields which the attacker uses to encode the destination address, the attacker will have to submit a log to DeepSight which contains these specific fields. This will allow an attacker to view the required response statistics for that probe in the DeepSight system, most importantly, the number of other clients that received the probe. Using these two simple modifications to our example algorithm, an attacker should be able to encode sufficient information in each probe such that the DeepSight network could be mapped in a single pass of probes.

myNetWatchman

Another important example of an Internet Sensor network that displays public statistics is myNetWatchman. The myNetWatchman sensor network groups the events of the past hour by source IP and lists them in the "Largest Incidents: Last Hour" report. For each source IP, this report lists the time, target subnet, source port, and destination port of the most recent event. The addresses monitored by myNetWatchman could be discovered in a single pass of probes using this or other available reports.

6.3 Other Types of Reports

Necessity of Event Counts

It is important to note that it is not even strictly necessary for the reports to include the number of events

network	bandwidth	probes sent	time to map
DeepSight	-	2.1 billion	single pass of probes
myNetWatchman	-	2.1 billion	single pass of probes
SANS ISC	T3	14 billion	4 days 16 hours
Modeled ISC	T3	20 billion	6 days 6 hours

Table 5: Essential mapping results.

matching some criteria, but only their presence or absence. In terms of the algorithm of the example attack as given in Section 4.2, it would no longer be possible to avoid sending probes to the last addresses in each interval. Instead, probes would always have to be sent to all the subintervals. Also, a different scheme would be needed to overcome the noise problem described in Section 4.3 (probably sending several probes to an interval and only marking it as containing a submitting address if the corresponding port consistently reports activity), but the attack could still be made to work.

Top Lists

One type of report commonly produced by log analysis centers is the "top list" or "hot list," essentially a list of the most common values of a field within the reports. For example, the "Top 10 Ports" report produced by the ISC is a list of the most frequently occurring destination ports among events in the past day. The number of values listed on the report may be a fixed number (in this case ten), or it may vary as in the case of reports that list all values occurring more often than some threshold. Such top list reports tend to be less useful for conducting probe response attacks for a couple reasons. Reports with a fixed length typically report very little total information. A probe response attack based only on the ISC "Top 10 Ports" report would take far too long to be feasible. Also, it may be necessary to generate a very large amount of activity to appear on a top list, also making the attack infeasible. Nevertheless, other such reports still merit a critical look to determine if they may be sufficient to launch a probe response attack. Such reports are likely to be more dangerous if they may be requested for various criteria (e.g., top ten ports used in attacks directed at a particular subnet rather than just top ten ports).

7 Countermeasures

7.1 Current Methods

Several methods are in use or have been proposed for preventing information published in reports from being misused.

Hashing and Encryption

One common technique is to hash some or all of the above fields. However, in general this does not impair the attack as the attacker (having generated the original probes) has a list of the possible preimages, which allows for an efficient dictionary attack. However, encrypting a field with a key not publicly available (or using a keyed hash such as HMAC-SHA1) would prevent the use of that field in a covert channel. Unfortunately, it would also prevent nearly any use of the information in that field by those who read the published reports for legitimate purposes. Prefix-preserving permutations [28] have been proposed a method for obscuring source IP addresses while still allowing useful analysis to take place. Obscuring source IP addresses with encryption (whether or not it is prefix-preserving) does not, however, prevent probe response attacks, as any of the other characteristics listed in Section 6.1 may be used.

Bloom Filters

The Bloom filters popular for storing a set of source IP addresses [25, 7] suffer from similar problems. In general, a Bloom filter storing a set of IP addresses is in fact safe from dictionary attacks due to the false positive feature of Bloom filters. Even with a relatively low rate of false positives, say 0.1 percent, the number of false positives resulting from checking all non-bogon IP addresses against the filter is on the order of two million (likely much more than the number of addresses actually stored in the filter). However, Bloom filters do not stand up to the iterations of a probe response attack. As an example, suppose some analysis center receives logs from monitored addresses and at the end of each time interval publishes a Bloom filter containing the source addresses observed. Sending probes to all non-bogon addresses with the destination address encoded in the source address, then checking for those addresses in the resulting Bloom filter would produce on the order of two million false positives (along with the true positives). Sending a second set of probes to all positives would reduce the number of false positives to about two thousand, and after re-probing those positives, approximately two false positives would remain. One more round would likely eliminate all remaining false positives, an accurate set of monitored addresses having been determined in four probe response iterations. There are of course the additional complications of noise and egress filtering, but this example illustrates that the number of false positives decreases exponentially with respect to the number of iterations of the probe response attack.

7.2 Information Limiting

Private Reports

The most immediately apparent way to prevent attackers from mapping the locations of the sensors is to limit the information published in the reports. The most heavy handed implementation of this strategy is to eliminate public reports entirely and only provide reports to persons and organizations that can be trusted to not attempt to map the sensor locations and not disclose reports to others. Clearly, such an approach severely limits the utility of the network. Only a select few obtain any benefit at all from the information collected and the analysis performed on that information.

Top Lists

The strategy of producing no public reports is probably overly cautious. It is likely possible to publish a variety of the "top list" style reports described in Section 6.3 without disclosing enough information to enable fast probe response attacks, provided some care is used. However, such lists do not provide anything approaching a complete picture of the activity within the Internet. In particular, publishing only top list style reports allows attackers to ensure their continued secrecy by intentionally limiting their activity to the extent necessary to stay off the lists.

Query Limiting

Alternatively, a log analysis center may provide full public reports or queries of all kinds, but limit the rate at which they can be downloaded. This may be accomplished by requiring payment for each report downloaded. The payment may be monetary, or it may take a more virtual form. Such virtual payments may be the computational effort required to solve a puzzle or the human interaction necessary to answer a CAPTCHA [39]. These transactional networks are similar to those proposed by researchers who are attempting to stem the flood of spam email. This may be used in conjunction with providing complete reports free of payment to any organizations that are completely trusted.

Sampling

Another strategy in limiting the information available to an attacker attempting to map the sensor locations is to sample the logs coming into the analysis center before generating reports from them. For example, the analysis center may discard every log it receives with probability $\frac{4}{5}$. Large scale phenomena such as worm outbreaks and port scanning should remain clearly visible in the reports [10], but a probe response attack would be more difficult. The probability of a single probe sent by an attacker to a monitored address resulting in a false negative would be $\frac{4}{5}$; to reduce this, the attacker would need to send multiple probes. If the attacker wished to reduce it to, say, 1 percent, they would need to send twenty probes. A twenty-fold increase in bandwidth is substantial, and a large number of false negatives would still likely result if the attacker attempted to map a network with hundreds of thousands of monitored addresses in that manner. Of course, this technique of sampling the incoming alerts does reduce the useful information produced by the analysis center. It has an advantage over the strategy of only publishing top list style reports, however. In this case there is no way for an attacker to be certain they will not appear in a report by limiting their activity. Even small amounts of malicious activity have a chance of being reported.

7.3 Other Techniques

Scan Prevention

An additional countermeasure which effectively renders our current algorithm useless is the widespread adoption of IPv6. With a search space of 128 bits, IPv6 greatly reduces the feasibility of TCP/UDP scanning and prevents the first stage of our attack from completing in a reasonable amount of time. Mechanisms for reducing the search space required for scanning in IPv6 such as exploiting dual-stacked networks, compiling address lists, and mining DNS have been previously addressed in [40]. While IPv6 is an effective countermeasure, the widespread adoption of IPv6 is out of the control of a sensor network and hence is an impractical countermeasure.

Delayed Reporting

By waiting to publish public reports for a period of time, an Internet sensor network can force an attacker to expend more time and bandwidth in mapping a network. To undertake a probe response attack in the face of delayed reporting, an attacker has two primary options: either wait to receive the responses from the most recent probes or continue probing using a nonadaptive probe response algorithm. Nonadaptive probe response algorithms do not rely on the responses of the previous round's probes to select the next intervals to probe, rather they continue probing and partitioning a likely larger search space than necessary under the assumption that a report will be produced at some point in time and that this report will allow for a much larger search space reduction than a single round of probe responses would have. However, since nonadaptive algorithms do not reduce the search space after each round of probes, they require significantly more probes to be sent and hence increase the bandwidth necessary for an attack to complete. We defer a full discussion of nonadaptive probing to future work. The other alternative of waiting for reports to be published is likely only possible if the delay is small. Of course, if a network can be probed in a single round then a waiting time of one week before publishing reports is not an effective countermeasure. Hence, delayed reporting should be used in conjunction with another technique which reduces the amount of information leakage. It should also be noted that the utility of a network designed to produce near real time notifications of new attacks is greatly reduced by delayed reporting.

Eliminating Inadvertent Exposure

Our final countermeasure is more of a practical suggestion rather than a general countermeasure. Internet sensor networks and log analysis centers should avoid publishing information about the specific distribution of addresses they monitor. A simple example should serve to highlight the primary types of information that must be eliminated from log analysis center descriptions. Take for example a log analysis center that publicly provides their complete sensor distribution, perhaps monitoring a single /8. In this case, we can simply probe all /8's and wait for a single probe to show up in the statistics reported by the sensor network. The singular fact that the log analysis center monitors a /8 network provides us with enough information to reduce the number of probes sent by our attack from several billion to 256! Even more complicated distributions like those provided in [20] should be eliminated as they provide very little useful information and make the attacker's job much easier. It should be noted that systems like honeypots, iSink, and network telescopes which often monitor contiguous address space are particularly vulnerable to this sort of inadvertent exposure.

8 Conclusion

In this paper we developed a general attack technique called probe response, which is capable of determining the location of Internet sensors that publicly display statistics. In addition, through the use of the probe response algorithm, we demonstrated critical vulnerabilities in several anonymization and privacy schemes currently in use in Internet analysis centers. We simulated a probe response attack on the SANS Internet Storm Center, as well as on various distributions of sensor nodes that could occur in other sensor networks, and were able to determine the set of monitored addresses within a few days with limited resources. Finally, we outlined the consequences of a successful mapping of Internet sensors, alternative reporting schemes, and countermeasures that defend against the attacks.

Our current mapping algorithm is an adaptive probe response algorithm as each round depends on the output of the previous round. On-going and future work includes developing and evaluating a nonadaptive approach for efficiently mapping Internet sensor networks that infrequently provide data sets or delay reports. Such networks include the University of Michigan Internet Motion Sensor [19, 20], CAIDA [2], and iSink [10]. Another issue to be investigated in future work is the effectiveness of proposed countermeasures.

Acknowledgments

We would like to acknowledge Johannes Ullrich of the SANS Institute for providing access to the DShield logs. We would also like to thank Eric Bach for his valuable insights and pointers and the anonymous reviewers for their suggestions. This work was supported in part by the U.S. Army Research Laboratory and the U.S. Army Research Office under grant number #DAAD19-01-1-0502. Jason Franklin performed this research while on appointment as a U.S. Department of Homeland Security (DHS) Scholar under the DHS Scholarship and Fellowship Program.

References

[1] The SANS Internet Storm Center, http://isc.sans.org.

[2] CAIDA, the Cooperative Association for Internet Data Analysis, http://www.caida.org.

[3] Computer Emergency Response Team. AirCERT. http://www.cert.org/kb/aircert/, 2003.

[4] C. Zou, L. Gao, W. Gong, and D. Towsley. Monitoring and Early Warning for Internet Worms. *Proceedings of CCS'03*, October 2003.

[5] The National Strategy to Secure Cyberspace, http://www.securecyberspace.gov.

[6] V. Yegneswaran, P. Barford, and S. Jha. Global Intrusion Detection in the DOMINO Overlay System. *Proceedings of the 2004 Network and Distributed System Security Symposium (NDSS 2004)*, February 2004.

[7] M. Locasto, J. Parekh, S. Stolfo, A. Keromytis, T. Malkin, and V. Misra. Collaborative Distributed Intrusion Detection. Tech Report CUCS-012-04, Department of Computer Science, Columbia University, 2004.

[8] N. Provos. Honeyd - a virtual honeypot daemon. *Proceedings of the 10th DFN-CERT Workshop*, February 2003.

[9] L. Spitzner. Know Your Enemy: Honeynets. *Honeynet Project*, http://project.honeynet.org/papers/honeynet.

[10] V. Yegneswaran, P. Barford, and D. Plonka. On the Design and Utility of Internet Sinks for Network Abuse Monitoring. *Proceedings of Symposium on Recent Advances in Intrusion Detection (RAID)*, September 2003.

[11] D. Moore. Network Telescopes: Observing Small or Distant Security Events. *Invited Presentation at the 11th USENIX Security Symposium (SEC 02)*, August 2002.

[12] V. Yegneswaran, P. Barford, and J. Ullrich. Internet Intrusions: Global Characteristics and Prevalence. *Proceedings of ACM SIGMETRICS*, June 2003.

[13] R. Pang, V. Yegneswaran, P. Barford, V. Paxson, and L. Peterson. Characteristics of Internet Background Radiation, *Proceedings of ACM SIGCOMM/USENIX Internet Measurement Conference*, October 2004.

[14] H. Kim and B. Karp. Autograph: Toward Automated, Distributed Worm Signature Detection. *USENIX Security Symposium*, 2004.

[15] C. Kreibich and J. Crowcroft. Honeycomb — Creating Intrusion Detection Signatures Using Honeypots. *Proceedings of the IEEE Symposium on Security and Privacy*, May 2004.

[16] S. Singh, C. Estan, G. Varghese, and S. Savage. The EarlyBird System for Real-time Detection of Unknown Worms. Technical Report CS2003-0761, UCSD, August 2003.

[17] Symantec DeepSight Threat Management System Technology Brief

[18] The myNetWatchman Project, http://www.mynetwatchman.com.

[19] The University of Michigan Motion Sensor, http://ims.eecs.umich.edu.

[20] M. Bailey, E. Cooke, F. Jahanian, J. Nazario, and D. Watson. The Internet Motion Sensor: A Distributed Blackhole Monitoring System. *Proceedings of the 12th Annual Network and Distributed System Security Symposium*, February 2005.

[21] D. Moore, C. Shannon, and J. Brown. Code-Red: A Case Study on the spread and victims of an Internet worm. *Proceedings of the 2nd ACM Internet Measurement Workshop*, pages 273-284. ACM Press, November 2002.

[22] D. Moore, V. Paxson, S. Savage, C. Shannon, S. Staniford, and N. Weaver. Inside the Slammer Worm. *IEEE Security and Privacy*, 1(4):33-29, July 2003.

[23] D. Moore, G. Voelker, and S. Savage. Inferring Internet Denial-of-Service Activity. *Proceedings of USENIX Security Symposium*, 2001.

[24] B. Bloom. Space/Time Trade-Offs in Hash Coding With Allowable Errors. *Communications of the ACM*, 1970. 13(7): p. 422-426.

[25] P. Gross, J. Parekh, and G. Kaiser. Secure "Selecticast" for Collaborative Intrusion Detection Systems. *Proceedings of the 3rd International Workshop on Distributed Event-Based Systems (DEBS'04)*, May 2004.

[26] A. Slagell, J. Wang, and W. Yurcik. Network Log Anonymization: Application of Crypto-PAn to Cisco Netflows. *Proceedings of the Workshop on Secure Knowledge Management 2004*, September 2004.

[27] G. Minshall. TCPdpriv: Program for Eliminating Confidential Information from Traces. Ipsilon Networks, Inc. http://ita.ee.lbl.gov/html/contrib/tcpdpriv.html

[28] J. Xu, J. Fan, M. Ammar, and S. Moon. Prefix-Preserving IP Address Anonymization: Measurement-based Security Evaluation and a New Cryptography-based Scheme. *Proceedings of the 10th IEEE International Conference on Network Protocols (ICNP'02)*, November 2002.

[29] S. Staniford, V. Paxson, and N. Weaver. How to 0wn the Internet in Your Spare Time. *Proceedings of the 11th USENIX Security Symposium*, 2002.

[30] P. Lincoln, P. Porras, and V. Shmatikov. Privacy-Preserving Sharing and Correlation of Security Alerts. *Proceedings of the 13th USENIX Security Symposium*, 2004.

[31] A. Slagell and W. Yurcik. Sharing Computer Network Logs for Security and Privacy: A Motivation for New Methodologies of Anonymization. *ACM Computing Research Repository (CoRR)* Technical Report 0409005, September 2004.

[32] R. Pang and V. Paxson. A High-level Programming Environment for Packet Trace Anonymization and Transformation. *Proceedings of SIGCOMM 2003*, August 2003.

[33] K. Carr and D. Duffy. Taking the Internet by storm. *CSOonline.com*, April 2003.

[34] The DShield Project, http://www.dshield.org.

[35] D.Z. Du, F. Hwang. *Combinatorial Group Testing and Its Applications*, World Scientific, Singapore, 2000.

[36] The Cymru Project Bogon List, http://www.cymru.com/Bogons/.

[37] Symantec Internet Security Threat Report, Volume VI, September 2004.

[38] B. Lampson. A Note on the Confinement Problem. *Communications of the ACM 16*, 10 (Oct. 1973), p. 613-615.

[39] L. von Ahn, M. Blum, N. Hopper, and J. Langford. CAPTCHA: Using Hard AI Problems for Security. *EUROCRPYT 2003*.

[40] T. Chown. IPv6 Implications for TCP/UDP Port Scanning. IETF Internet Work In Progress Draft, July 2004.

Notes

[1] The authors verified this by sending a number of packets to external hosts submitting to ISC and verifying that the activity appeared in the port reports as expected.

[2] We do not bother waiting to complete a TCP handshake, as this is not necessary for activity to be reported.

[3] Briefly, we round $\frac{n}{k}$ to the nearest integer, adjusting as necessary to ensure the total number of ports used is n.

[4] The minimum time encountered to determine the exact set of addresses monitored by the ISC was found to be 2 days and 8 hours, but the bandwidth required makes this case unreasonable.

[5] The sizes of clusters of sensor addresses in the ISC are fit extremely well by a power law, motivating the use of the Pareto distribution for cluster sizes in the model.

[6] At four bytes per address, a list of 700,000 IP addresses is only about 2.7MB, and may be compressed to an even smaller size.

[7] We assume the whole destination IP address is never reported, otherwise the attack is trivial.