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Cyber Crime Scene Investigations (C^2SI) through Cloud Computing

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***Abstract*—Cloud computing brings opportunities for network forensics tracing Internet criminals in the distributed environment. We may use the new "pay-as-you-go" model of the cloud computing to deploy the on-demand cyber surveillance sentinels and conduct distributed traceback in complicated cyber crime scene investigations. To trace criminals abusing anonymous communication networks such as Tor, law enforcement can deploy high-bandwidth Amazon EC2 sentinels into the Tor network. Some sentinels are configured as Tor entry guards and others work as Tor exits nodes. With the high bandwidth and appropriate number of such sentinels, we can achieve a required probability that a Tor circuit passes through an entry sentinel and an exit sentinel in order to capture the suspects. The proposed "pay-as-you-go" traceback model is cost-effective since the investigation may last for just hours with effective traceback techniques. Our experiments demonstrate the feasibility of this new traceback strategy through the cloud.**

***Keywords*-Cloud Computing, Network Forensics, Traceback, Tor, Sentinels**

I. Introduction

Cloud computing brings opportunities for network forensics tracing Internet criminals in the distributed environment. We may use the new "pay-as-you-go" model of the cloud computing to deploy the on-demand sentinels and conduct distributed traceback in complicated cyber crime scene investigations.

Cloud computing provides users different venues and services to conduct computing on the Internet. Cloud computing can be viewed as ready-to-go information technology for purchase as a service over the network [1]. Such a computing model boasts infinite pay-as-you-go computing resources available on demand for any span of rent time [2]. Users don't need to purchase hardware, software and configure them locally. Via cloud computing, software, hardware and the configured system are purchased as a service. Users can rent a server or thousands of servers via cloud computing providers around the world. The demanded computing service can be started and stopped at any time at will. The application running with the cloud can be a datacenter such as email and corporate database or CPU thirsty computing on powerful servers.

Cloud computing service is often delivered through virtual machines (VM) because of VM's flexibility and ready-to-go nature. Different applications services can be delivered as ready-to-go packages or assembled across the Internet to achieve a specific computing goal. The computing can scale down and up via the cloud computing application software in charge of the service software and hardware.

Various cloud computing services are currently available. Amazon EC2 (Amazon Elastic Compute Cloud) [3] is at one end of the service spectrum. EC2 provides whole VMs for purchase. A user has full control and root privilege of the VMs. Read-to-go software are also available for purchase to run on VMs. The billing of the service is based on the rent time and network bandwidth usage. Google App Engine [4] is at the other end of the application spectrum. Users develop web sites via Google AppFabric [6]. Windows Azure provides a Windows-based environment for running applications and storing data on servers in Microsoft data centers. SQL Azure provides data services in the cloud based on SQL Server. Windows Azure platform AppFabric provides cloud services for connecting applications running in the cloud or on premises.

In this paper, we explore the application of digital forensics through cloud computing. As wireless, mobile computing, and the Internet become pervasive and ubiquitous, the number of cyber crimes has also been increasing drastically. These crimes include sexual exploitation of children, intellectual property theft, identity theft, financial fraud, and espionage, etc. Digital forensics studies techniques that enable the investigation of an alleged crime or policy violation involving digital data. It serves an important role in industry, federal and state law enforcement, and other national cyber-defense forces.

We can divide digital forensics techniques into two categories: computer forensics and network forensics. Computer forensics is a relatively established area. The traditional consensus was that computer forensics is about collecting and analyzing evidence on standalone mediums such as hard drives, flash memory, computer memory, etc. As the technology advances, today's PDAs and smartphones also possess large storage capability. Techniques collecting evidence from these devices can also be included into the category of computer forensics.

Network forensics is a growing area of digital forensics. Network forensics is about tracing and locating criminals on the Internet. Cyber crimes often involve complicated crime-scene investigations. Criminals may abuse professional anonymous communications systems such as Tor [7], [8], Anonymizer [9], I2P [10], BitBlinder (Anonymous BitTorrent) [11] and AnoTorrent (anonymous P2P Bittorrent) [12], which were originally designed for protecting network users from identity theft and profiling. Network forensics over such systems again requires the application of cutting-edge research. Collecting evidence from networks is already a challenging problem since the evidences may be volatile: packet logging is a formidable task given the extremely large volume of network data and network packets are often not logged. Tor and Anonymizer are the most popular two anonymous communication networks while the number of users of other systems and networks is limited and their core techniques for anonymity are also similar to Tor and Anonymizer. Without loss of generality, we use Tor as an example to explain our research for forensic investigation of anonymous communication systems whenever necessary.

This paper is focused on network forensics. We explore the opportunities that cloud computing brings to us in tracing cyber criminals hiding in the dark cloud such as abused anonymous communication systems. We propose to deploy on-demand Tor sentinels into the cloud. e.g., those provided by Amazon EC2. When crime activities are intense over the dark cloud and it is time to conduct network forensic investigations, Tor sentinels will be activated. Such investigations utilize the pay-as-you-go model of cloud computing and they are cost-effective since the investigation can last for just hours with effective traceback techniques. The law enforcement does not need to deploy massive surveillance infrastructure which can be idle for most of time and incur overwhelming maintenance cost. Although Planetlab [13] can be one type of cloud computing platform and hosts the sentinels, it has limited bandwidth capability, has rigid policies on its usage and is not appropriate for the network forensic traceback. For example, Planetlab nodes cannot be used as Tor exit sentinels, which are critical for the success of the traceback.

This paper makes the following contributions:

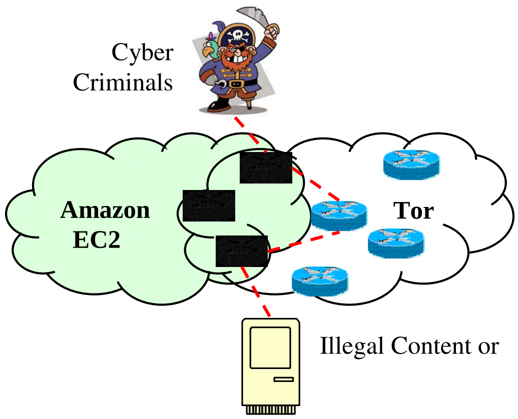
- We are the first to formally propose to use cloud computing services to help the cyber crime scene investigations (C^2SI) and define a set of meaningful problems. Sentinels can be set up within the cloud and monitor crimes on the Internet in a cost-effective way.
- We are the first to analyze how to set up Amazon EC2 sentinels monitoring the abuse of the Tor network. Such abuse is throttling the healthy Tor development. For traceback through Amazon EC2 nodes, our theoretical results fully match the results from Tor algorithm simulations.

The rest of this paper is organized as follows: Section II introduces the basic idea of traceback through the cloud. Section III analyzes optimization of cloud computing investment for maximum traceback results using Amazon EC2 over Tor. Section IV evaluates the strategy of network forensics through cloud computing. We conclude this paper in Section V.

II. Traceback through the Cloud

A. *Basic Idea*

Figure 1 illustrates the basic idea of traceback through the cloud. Law enforcement deploys high-bandwidth surveillance sentinels by purchasing the cloud computing service from providers such as Amazon. Those sentinels become part of the anonymous communication network such as Tor, which is the focus of this paper. Some are configured as Tor entry guards and others work as Tor exits nodes. With the high bandwidth and appropriate number of such sentinels, we can achieve a required probability that a Tor circuit passes through an entry sentinel and an exit sentinel. The law enforcement can then employ various efficient and effective traceback techniques [14], [15], [16] and determine if the evil attacks the victim server or downloads illegal content from a server.



We introduce the EC2 IP range below and discuss the optimization problem in Section III.

B. IP Range of Amazon Elastic Compute Cloud

Within Amazon Elastic Compute Cloud (EC2), Elastic IP addresses are static IP addresses designed for dynamic cloud computing. An Elastic IP address is associated with a user account not a particular instance, and users control that address until they choose to explicitly release it. To provide fault tolerance, EC2 provides its virtual instances across multiple data centers organized in so-called region and availability zones. Region is comprised of several availability zones. Two virtual instances running in different availability zones are guaranteed to be executed in different data centers. Of the eight availability zones, six are located in the U.S. East, one is in the U.S. West and one are in Europe.

Unlike traditional static IP addresses, however, Elastic IP addresses allow users to mask instance or Availability Zone failures by programmatically remapping user public IP addresses to any instance in user accounts. Rather than waiting on a data technician to reconfigure or replace the user host, or waiting for DNS to propagate to all customers, Amazon EC2 enables users to engineer around problems with a user instance or software by quickly remapping an Elastic IP address to a replacement instance [3].

To find the IP range of Amazon EC2 robustly and flexibly, we can google the keywords "Amazonaws", "IP Range", "Net Range" and so on to find the public IP addresses or domain names of the Amazon Web Services. Then, we use whois [17] to find out the IP ranges corresponding to the known EC2 domain names. Table I shows that the searched IP ranges by using Google and Whois are almost the same as the Amazon EC2 official IP range [18].

Table I
AMAZON EC2 PUBLIC IP RANGES

Region	Official IP Ranges	IP Ranges from web
US East (Northern Virginia)	204.236.128.0/18 72.44.32.0/19 67.202.0.0/18 75.101.128.0/17 174.129.0.0/16 204.236.192.0/18	204.236.128.0/18 72.44.32.0/19 67.202.0.0/18 75.101.128.0/17 174.129.0.0/16 204.236.192.0/17
US West (Northern California)	216.182.224.0/20	204.236.128.0/17
EU (Ireland)	79.125.0.0/17	79.125.0.0/18

From Table I, we can see that EC2 has a wide range of IPs and meet the requirement of traceback via sentinels.

III. OPTIMIZATION OF CLOUD COMPUTING INVESTMENT FOR MAXIMUM TRACEBACK RESULTS

In this section, we first present the Tor path selection algorithm. We then discuss how to optimize the catch probability given a fixed number of Amazon EC2 nodes as the cloud computing investment.

A. Tor Path Selection Algorithm

Algorithm 1 presents the path selection algorithm which chooses routers in a specific order given a desired path length that is 3 by default. Tor does not choose the same router twice for the same path [19]. From Algorithm 1, we know that to create a circuit, Tor selects an exit node, an entry node and then a middle node in order. Algorithm 2 presents the algorithm of *Preprocessing a List for Selecting the Exit Node*. To improve the circuit throughput, Tor uses bandwidth weighted Algorithm 3 to choose the exit and entry node from the corresponding candidates. Algorithm 4 describes the selection of entry or middle nodes for a circuit.

Algorithm 1 Tor Path Selection Algorithm

```
Create a new circuit and initialize global circuit ID, etc.
Add the circuit into the global circuit list
Decide a suitable length for the circuit
if one hop tunnel is predefined then
    The circuit length is one
else
    The circuit length is three by default
end if
if The option ‘ExitNodes’ in the configuration file is defined then
    Use the defined exit node as the exit router
else
    Exclude the chosen exit node based on Algorithm 2 and select an exit node based on Algorithm 3
end if
Select an exit node based on Algorithm
Exclude the chosen exit node and current entry nodes then select an entry node based on Algorithm 4
Exclude the chosen exit node and current middle nodes then select a middle node based on Algorithm 4
```

Algorithm 2 Preprocess a List for Selecting the Exit Node

```
Exclude clients that are (in case that client is an OR node) possible exit nodes
Exclude nodes that are not running or remarked as a bad exit node
Exclude nodes that are not meeting capacity or uptime requirements
Exclude nodes that are remarked as invalid
Exclude exit nodes whose policies reject all traffic
```

B. Optimization of the Number of EC2 Sentinels

Assume that the attacker chooses k EC2 sentinels and sets up these nodes as surveillance Tor sentinel nodes in the Amazon Elastic compute cloud. Also, assume that the bandwidth of all onion routers comprises a set $\{B_1, B_2, ...B_k, B_{k+1}..., B_{k+N}\}$, where $\{B_1 \geqslant ... \geqslant B_{k+N}\}$, that is the bandwidth of the sentinel onion routers

Algorithm 3 Choose the Node based on Bandwidth

Require:
(a) all_{bw}, the total bandwidth of the nodes in the node list (b) $exit_{bw}$, the total bandwidth of the exit nodes in the node list (c) $guard_{bw}$, the total bandwidth of the guard nodes in the node list (d) q, the number of the nodes in the list (e) $b[i]$, the bandwidth of the i^{th} node in the list (f) $exit_w$, the weight of the exit nodes (g) $guard_w$, the weight of the guard nodes (h) bw, the weighted bandwidth of the nodes (i) $total_{bw}$, the totally weighted bandwidth of the nodes (j) $rand_{bw}$, the random sampling bandwidth value from the $total_{bw}$

Ensure: Find a suitable node from the node list

```
Derive a list of qualified running nodes
Count $all_{bw}$, $exit_{bw}$ and $guard_{bw}$
if try to find a exit node then
    $exit_w = 1$
else
    $exit_w = 1 - all_{bw}/(3 \times exit_{bw})$
end if
if try to find a guard node then
    $guard_w = 1$
else
    $guard_w = 1 - all_{bw}/(3 \times guard_{bw})$
end if
if $exit_w < 0$ then
    $exit_w = 0$
end if
if $guard_w < 0$ then
    $guard_w = 0$
end if
for $i = 1 : q$ do
    if the node is both exit and guard node then
        $bw = b[i] \times guard_w \times exit_w$
    else if the node is entry then
        $bw = b[i] \times guard_w$
    else if the node is exit then
        $bw = b[i] \times exit_w$
    else
        $bw = b[i]$
    end if
    $total_{bw} = total_{bw} + bw$
end for
Randomly sample a bandwidth $rand_{bw}$ from $total_{bw}$
for $j = 1 : q$ do
    if the node is both exit and guard node then
        $temp = temp + b[i] \times guard_w \times exit_w$
    else if the node is entry then
        $temp = temp + b[i] \times guard_w$
    else if the node is exit then
        $temp = temp + b[i] \times exit_w$
    else
        $temp = temp + b[i]$
    end if
    if $temp > rand_{bw}$ then
        return the $i^{th}$ node
    end if
end for
```

Algorithm 4 Selection of an Entry/Middle Node for a Circuit

```
Derive a list of qualified running nodes
if Bandwidth or a guard node is required then
    Use a bandwidth weighted algorithm based on Algorithm 3 to choose one
else
    Choose middle nodes randomly
end if
```

$\{B_1, ..., B_k\}$ have the maximum bandwidth within the set. Assume all sentinels advertise the highest bandwidth[1], i.e., $B_1 = B_2 = ... = B_k = b$. Denote B as the total bandwidth of the onion routers, i.e. $B = \sum_{i=1}^{k+N} B_i$. Recall there are four types of routers in the Tor network: entry, middle, exit and *both entry and exit* router (denoted as *EE* router). To derive the maximum probability P, denoted as *catch probability*, that a circuit chooses the EC2 sentinels as entry and exit routers, we should carefully deploy the sentinels as Tor entry routers, exit routers or EE routers.

Our optimization problem is: given k EC2 sentinels, maximize catch probability P by allocating appropriate number of sentinels as exit, entry and EE Tor nodes.

We propose three schemes of configuring EC2 sentinels as different types of onion routers to address this optimization problem and will evaluate and identify the best scheme in Section IV.

1) Scheme 1: Assume that we configure EC2 nodes as either Tor exit routers or entry routers (not as EE routers). Denote the bandwidth of total original entry routers, EE routers and exit routers as B_{entry}, B_{EE} and B_{exit}, respectively. An exit onion router with bandwidth B_i will be chosen with a probability $p_i = B_i/B_{exit}$, based on weighted bandwidth routing Algorithm 3. Denote the number of exit sentinels as e. Based on Algorithm 3, the weight can be derived as follows,

$$exit_{w1} = \begin{cases} 1 - \frac{B}{3 \cdot (B_{exit} + B_{EE} + e * b)} & : \ exit_{w1} > 0 \\ 0 & : \ exit_{w1} \leqslant 0 \end{cases} \tag{1}$$

$$entry_{w1} = \begin{cases} 1 - \frac{B}{3 \cdot (B_{entry} + B_{EE} + (k-e) * b)} & : \ entry_{w1} > 0 \\ 0 & : \ entry_{w1} \leqslant 0 \end{cases} \tag{2}$$

Then the catch probability can be calculated as follows,

$$P_1(e) = \frac{e \cdot b}{B_{exit} + entry_{w1} * B_{EE} + e \cdot b} \cdot \frac{(k-e) \cdot b}{B_{entry} + exit_{w1} * B_{EE} + (k-e) \cdot b} \tag{3}$$

2) Scheme 2: Assume that we configure all of the EC2 nodes as EE sentinels, i.e., k EE sentinels. According to

[1] The Tor project released a new version that changes the upper-bound of high bandwidth to 10MB/s on August 30, 2007

Algorithm 3, the weight can be derived by,

$$exit_{w2} = \begin{cases} 1 - \frac{B}{3\cdot(B_{exit}+B_{EE}+k*b)} & : \quad exit_{w2} > 0 \\ 0 & : \quad exit_{w2} \leqslant 0 \end{cases} \quad (4)$$

$$entry_{w2} = \begin{cases} 1 - \frac{B}{3\cdot(B_{entry}+B_{EE}+k*b)} & : \quad entry_{w2} > 0 \\ 0 & : \quad entry_{w2} \leqslant 0 \end{cases} \quad (5)$$

Then the catch probability can be calculated as follows,

$$P_2(e) = \frac{entry_{w2} \cdot k \cdot b}{B_{exit} + entry_{w2} * (B_{EE} + k \cdot b)} \cdot$$

[redacted]

as the exit routers, the calculated as follows,

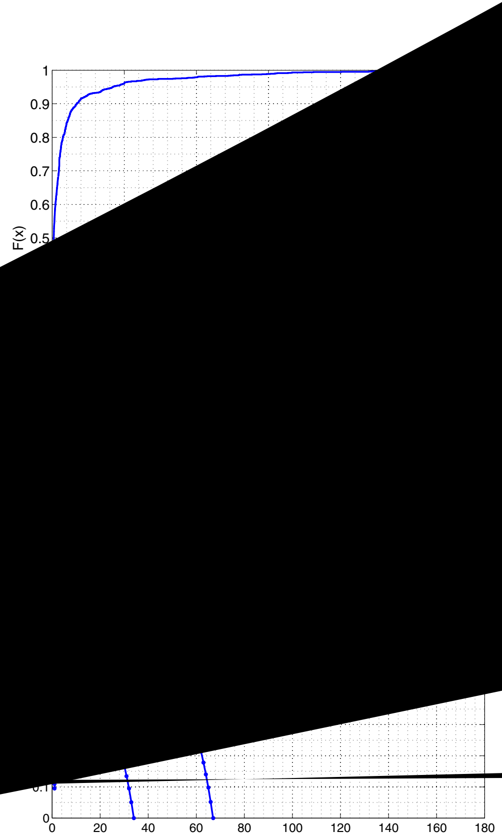
$$P_3(e) = \frac{e_1 \cdot b}{B_{exit} + entry_{w3} * (B_{EE} + e_3 \cdot b) + e_1 \cdot b} \cdot \frac{(exit_{w3} \cdot e_3 + e_2) \cdot b}{B_{entry} + exit_{w3} * (B_{EE} + e_3 \cdot b) + e_2 \cdot b}$$
$$+ \frac{entry_{w3} \cdot e_3 \cdot b}{B_{exit} + entry_{w3} * (B_{EE} + e_3 \cdot b) + e_1 \cdot b} \cdot \frac{(exit_{w3} \cdot (e_3 - 1) + e_2) \cdot b}{B_{entry} + exit_{w3} * (B_{EE} + (e_3 - 1) \cdot b) + e_2 \cdot b} \quad (9)$$

IV. Evaluation

Both simulations of Tor algorithms and theoretical calcuations are conducted to verify our traceback approaches through cloud computing in Section III. The two results fully match each other. We will not differentiate them below.

We downloaded the information of the nodes from the Tor network on Feb 8, 2010. There were 1513 onion routers in the Tor network. Figure 2 shows the empirical cumulative probability function. The maximum bandwidth in Tor network at that time is around $5MB/s$. The bandwidth of 90% of onion routers are less than $350KB/s$.

In scheme 1, by applying Algorithm 3, we can derive the probability P, denoted as *catch probability*, that a circuit chooses the sentinel onion routers as entry and exit onion routers. Figure 3 shows P given $p \in \{2\%, 4\%, 6\%, 8\%, 10\%\}$, the percentage of EC2 sentinels within Tor, that is, we need $\{34, 67, 101, 134, 168\}$ EC2 nodes, respectively. Then we select the maximum P and



In Scheme 2, we deploy all EC2 sentinels as EE onion routers. As shown in Figure 5, when we deploy 168 EC2 nodes, the probability P in Scheme 2 is almost equal to the results in scheme 1. In Scheme 3, we deploy the Amazon EC2 sentinels as exit onion routers, entry onion routers and EE onion routers. According to our investigation, when we derive the maximum probability P, the number of the EE onion routers is zero. Specifically, when P reaches the maximum, Scheme 3 is the same as Scheme 1.

In addition, to increase the probability that a circuit chooses the EC2 sentinels as exit onion routers and entry onion routers, we should deploy the IP address range of the EC2 nodes in different class C and districts. Amazon EC2 can meet this requirement as we investigated in Section II.

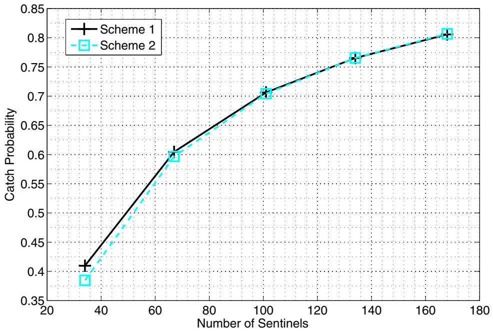


Figure 5. Catch Probability vs. Number of Sentinels

V. Conclusion

In this paper, we propose to utilize the cloud computing for on-demand cyber crime scene investigations. In a time of intense crimes within anonymous communication networks such as Tor, law enforcement may purchase tens of Amazon EC2 VMs, which join the Tor network as sentinels. Those sentinels act as entry and exit nodes of Tor circuits and will be able to determine the attack sources within appropriate traceback techniques. From our study, with 168 EC2 sentinels, we can achieve over 99% catch probability if the suspect makes 3 connections. As the traceback utilizes the "pay-as-you-go" model of cloud computing and the network forensics session may last for a few hours or a few days, the strategy is cost effective.

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