

UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

Behavioral Malware Detection Approaches for Android

A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
Degree of
DOCTOR OF PHILOSOPHY

By

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Norman, Oklahoma
2015

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A DISSERTATION APPROVED FOR THE
Department of Computer Science and Engineering

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Dedication

This dissertation is dedicated to .

Acknowledgements

This work has been possible because of a number of individuals. First of all, I would like to express my sincere gratitude to my faculty advisor Dr. Mohammed Atiquzzaman for his expert advice, patience and continuous supervision throughout my PhD studies, which made this work possible.

I am truly grateful to my committee members: Dr. John K. Antonio, Dr. Changwook Kim, Dr. Dean Hougen and Dr. Zahed Siddique for their valuable advice and time to review the dissertation. Their comments and suggestions have been very helpful to improve the quality of this dissertation.

I am also thankful to all the faculty and staff members of the School of Computer Science at the University of Oklahoma for providing a supportive environment for my study. Moreover, numerous discussion with my fellow researchers Dr. Abu Zafar Shahriar, Mr. Sazzadur Rahman, Syed Maruful Huq and Yasmin Jahir, and their technical expertise led to the improvements of this work.

The author would like to acknowledge the financial support of National Aeronautics and Space Administration (NASA) to carry out this project.

Last but not least, I would like to thank my wife Nusrat and my daughter Tasneem for accompanying and supporting me through all the tough times, and my parents and sister for providing moral support.

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Abstract

Today mobile computing has become a necessity and we are witnessing explosive growth in the number of mobile devices accessing the Internet. To facilitate continuous Internet connectivity for nodes and networks in motion, mobility protocols are required and they exchange various signaling messages with the mobility infrastructure for protocol operation. Proliferation in mobile computing has raised several research issues for the mobility protocols. First, it is essential to perform cost and scalability analysis of mobility protocols to find out their resource requirement to cope with future expansion. Secondly, mobility protocols have survivability issues and are vulnerable to security threats, since wireless communication media can be easily accessible to intruders. The third challenge in mobile computing is the protection of signaling messages against losses due to high bandwidth requirement of multimedia in mobile environments. However, there is lack of existing works that focus on the quantitative analysis of cost, scalability, survivability and security of mobility protocols.

In this dissertation, we have performed comprehensive evaluation of mobility protocols. We have presented tools and methodologies required for the cost, scalability, survivability and security analysis of mobility protocols. We have proposed a dynamic scheduling algorithm to protect mobility signaling message against losses due to increased multimedia traffic in mobile environments and have also proposed a mobile network architecture that aims at maximizing bandwidth utilization. The analysis presented in this work can help network engineers compare different mobility protocols quantitatively, thereby choose one that is reliable, secure, survivable and scalable.

Chapter 1

Introduction

Next generation networks are gradually converging towards the all-IP networks which can enable true global mobility and Internet connectivity to mobile devices.

1.1 Introduction

Internet Protocol (IP) is the underlying communication protocol that allows an end host to get connected to other hosts over the public Internet. Therefore, to facilitate continuous Internet connectivity for mobile nodes, Internet Engineering Task Force (IETF) proposed Mobile IPv6 [1], an IP-based mobility protocol.

This aggregated mobility management can significantly reduce signaling requirement and power consumption.

1.2 Motivation and Problem Statement

In a mobile computing environment, a number of *network parameters* (such as, network size, mobility rate, traffic rate) influence the signaling costs related to mobility management. With the rapid growth and popularity of mobile and wireless networks,

Finally, mobility protocols can be vulnerable to security threats.

1.3 Objectives

The *objectives* of this research are as follows:

- The first objective of this research is to perform a comprehensive cost and scalability evaluation of the
- The second objective of this research is the quantitative evaluation of survivability of the mobility infrastructure and the associated components.
- The fourth objective of this research is to protect mobility protocols from security threats.
- Finally, mobility protocols require a realistic mobility model that can mimic the movement pattern of nodes in motion.

1.4 Contributions

The *contributions* of the dissertation are summarized as follows:

- Perform entity-wise cost evaluation of host and network mobility protocols.
- Perform quantitative scalability analysis of host and network mobility protocols.
- Perform multi-class queuing analysis and propose a dynamic scheduling algorithm to protect crucial control messages (of mobility management) against losses.

1.5 Organization of the Dissertation

The rest of the dissertation is organized as follows. Chapter ?? presents a review of host and network mobility protocols.

Chapter 2

Literature Survey

2.1 Related Works

All the related works analyzed are listed here.

2.1.1 Mobile Malware Evolution, Detection and Defense

- *Published in:* EECE 571B, TERM SURVEY PAPER, APRIL 2012
- *Author(s):* Srikanth Ramu
The Institute for Computing, Information and Cognitive Systems (ICICS),
University of British Columbia
- *Summary:*
The Research briefly summarizes the history of mobile malware, specifics of mobile security when compared with computer security, various attack vector and attack models, various detection techniques for specific mobile devices, the defense mechanisms to control mobile malware.
- *Positive Outcomes:*
 1. Works as a baseline for related research.
 2. Clearly distinguishes among various malicious applications (e.g grey-wares etc.)

3. Defines various detection approaches.
 4. Brings up newer models of malware posting like mal-advertising etc. to focus
- *Limitations:* It doesnt specify a definitive approach, rather generic.

2.1.2 Detection of Mobile Malware in the Wild

- *Published in:* IEEE Explore ISSN - 0018-9162 September 2012
- *Author(s):* Mahinthan Chandramohan and Hee Beng Kuan Tan
School of Electrical and Electronic Engineering,
Nanyang Technological University, Nanyang Avenue, Singapore
- *Summary:* In this paper a survey of techniques that are used to detect mobile malware in the wild is presented and the limitations of current techniques are discussed.
- *Positive Outcomes:*
 1. Successfully classifies some malwares according to their behavior.
 2. Clearly outlines static and dynamic analysis.
 3. Suggests cloud nased detection, resulting in off device analysis for battery-life efficiency.
- *Limitations:* Suggests that permission analysis can be used for pre-screening, where in the android system, without giving permission, an application cannot be installed to check its behaviour.

2.1.3 Dissecting Android Malware: Characterization and Evolution

- *Published in:* IEEE Symposium on Security and Privacy, San Francisco, CA, May 20-23, 2012, pp. 95109.

- Author(s): Yajin Zhou and Xuxian Jiang
Department of Computer Science
North Carolina State University

- *Summary:*

There are three goals and contributions of this paper. First, this paper presents the first large collection of 1260 Android malware samples (that we used in our research, see Acknowledgement) in 49 different malware families, which covers the majority of existing Android malware, ranging from August 2010 to October 2011. Second, based on the collected malware samples, it performs a timeline analysis of their discovery and characterize them based on their detailed behavior breakdown, including the installation, activation, and payloads. Third, it performs an evolution-based study of representative Android malware, which shows that they are rapidly evolving and existing anti-malware solutions are seriously lagging behind.

- *Positive Outcomes:*

1. Successful creation of data tables for malwares clearly stating their repository (official market/free repository); classification based on installation, activation, malicious payloads, permission issues; evolution of specific malwares through time (since there discovered)
2. Evaluation of performance for 4 known antivirus on Android phone.

- *Limitations:* Permission comparison among different apps (malwares and non-malwares) which is inadequate to form definitive outcome, as we have learnt in our research.

2.1.4 Detecting Android Malware on Network Level

- *Published in:* Technical representation UC Santa Barbara, 2012
- *Author(s):* Danny Iland, Alexander Pucher, Timm Schauble
- *Summary:*

The papers analysis of packet traces focuses on finding information leakage in HTTP traces and identifying connection attempts to command-and-control servers. Conversions containing International Mobile Equipment Identity number (IMEI), phone number or credit card information were tracked. If no abnormalities are detected so far, the packet dump is compared manually to a dump generated by the uninfected VM template image to determine whether the sample was not detected or simply inactive.

- *Positive Outcomes:*
 1. Blacklisting DNS servers for possible malicious repository.
 2. String matching on HTTP header flags, GET, POST requests for possible malicious data transfer.
 3. The researchers were able to observe client-side communication using mock DNS and HTTP server responses. In total, 18 samples were investigated, generating traces compared against the patterns of identifying information. Of those, 8 samples were detected, 2 evaded detection and 8 samples failed to execute in the virtualized environment.
- *Limitations:*
 1. Addresses cannot be black-listed until a malicious application is identified

and the connections it makes are analyzed.

2. Use of Android x86 virtual machines also introduces several limitations. An Android x86 VM is not a cellphone, it does not support text messages, and has a non-standard IMEI and IMSI. Requests of IMEI and IMSI return the null value.

2.1.5 Detection of Malicious Android Mobile Applications Based on Aggregated System Call Events

- *Published in:* International Journal of Computer and Communication Engineering, Vol. 3, No. 2, March 2014
- *Author(s):* You Joung Ham and Hyung-Woo Lee
Dept. of Computer Engineering, Hanshin University, Rep. of Korea.
- *Summary:*

The research suggests a method to distinguish Android-based malicious apps based on the system call event pattern internally activated after running suspicious malicious applications. It analyzed the malicious system call event pattern selected from Android Malware Genome Project. The actual system call patterns are extracted from the normal and malicious apps on Android-based mobile devices. And then, feature events were aggregated to calculate a similarity analysis between normal and malicious event set.
- *Positive Outcomes:*
 1. Found pattern of normal and malicious system call events.
 2. classifies apps based on malicious behavior based on system call events.
 3. makes activity pattern comparison between normal and malicious apps.
 4. Established Quantifiable similarity among malware examples.

- *Limitations:*

Identifies 17 system call events which do not occur in normal application, are found in malicious applications. Therefore, any given apps could be suspected as malicious mobile application if the 17 kinds of system call events above have occurred simultaneously in the application. But in our research we found out that there is at most 2/3 system calls that can correspond to such decision.

2.1.6 Identifying android malicious repackaged applications by thread-grained system call sequences

- *Published in:* Computers and Security, vol. 39, p. 340 to 350
- *Author(s):* Ying-Dar Lin , Yuan-Cheng Lai , Chien-Hung Chen a, Hao-Chuan Tsai

- *Summary:*

Based on Malicious Repackaged Applications (MRAs), this work proposes a mechanism SCSdroid (System Call Sequence Droid), which adopts the thread-grained system call sequences activated by applications. The concept is that even if MRAs can be camouflaged as benign applications, their malicious behavior would still appear in the system call sequences. SCSdroid extracts the truly malicious common subsequences from the system call sequences of MRAs belonging to the same family. Therefore, these extracted common subsequences can be used to identify any evaluated application without requiring the original benign application.

- *Positive Outcomes:* SCSdroid achieved up to 95.97% detection accuracy, i.e., 143 correct detections among 149 applications.
- *Limitations:* No significant limitations.

Chapter 3

Detection using network traffic analysis

In this chapter, we will discuss about malware detection using Network traffic analysis. This chapter contains 2 sections. Section 3.1 describes the outline of our strategy, and in section 3.2, we describe the procedure in details.

3.1 Strategy of Malware Detection

At first, we created log of URLs that are contacted by applications for a specific period of time. Then we tried to match each entry (URL) of the log with a list of known malicious domains. If a match is found, the application that contacted the malicious domain is a malware itself or has been affected by one.

3.1.1 Creating the App-URL table

App-URL table is a history/log of all attempts made by all applications to communicate with remote servers over HTTP. The table consists of **(url, app)** entries. Each HTTP request maps to a single entry, where **url** is the URL which is contacted, and **app** is the application that originated the HTTP request.

This process is further subdivided into four tasks:

3.1.1.1 Packet dumping

We have recorded all incoming and outgoing network packets to/from the android device for specific duration of time. This creates a packet dump file that contains information of which port number (of the mobile device) is accessing which URL.

3.1.1.2 Netstat Logging

To relate port numbers with applications, we periodically executed *netstat* [?] command throughout the duration of packet dumping and saved the outputs. Netstat gives information of which port number is being used by which application when the command is executed.

3.1.1.3 Extracting necessary information from packet dump

We do not take all packets into consideration. We are only interested in HTTP packets (and only requests, not responses). So we have filtered out all other packets from the packet dump we generated at the first step. We took only three fields from each packet: time, originating port and full request URI. This gives a time-sequenced log of port numbers and URIs that a port tried to connect to.

3.1.1.4 Aggregating packet dump and netstat logs

We have so far obtained two separate mappings: *application vs. port number* from netstat logs, and *port number vs. URL* from packet dump. We aggregate these two maps to create a time-sequenced log of applications and the URLs each application tried to contact (The App-URL table).

3.1.2 Matching the URLs with Domain-blacklists

We search the URLs in the App-URL table for known malicious domains. If an application tries to connect to a rogue domain (URL), we flag it as a malware. We can also enrich our blacklist by adding other domains contacted by a flagged application.

These steps are discussed in detail in the following section.

3.2 Details of Malware Detection steps

Our first step is to create an App-URL table. In this table, each row of the table indicates an attempt to make an HTTP connection by any application. We store the time, the application's unique identifier (package name), and the URL which was contacted.

3.2.1 Creating the App-URL table

3.2.1.1 Packet dumping

We need to use a software for recording all incoming or outgoing traffic (packets) of the android device. This can be done using *Wireshark* [?] in a computer which is connected to the same local network of the android device.

Alternatively, we can use a similar application in the mobile device. We have used *Shark for Root* [?] for this purpose. A rooted device is not required for this step. Non-rooted devices can use other applications, such as *tPacketCapture*, which captures packets by creating a VPN and directing all traffic through the VPN. We captured packets for a specific amount of time. This step produces a packet dump (*.pcap*) file.

3.2.1.2 Netstat Logging

The packet dump does not directly detect which packet is originated from/destined for which mobile application. The system differentiates packets of different applications by port numbers (source port for outgoing packets or destination port for incoming packets). Hence, we need to know which ports were being used by which applications when the packet was captured. We used the UNIX tool *netstat* [?] to get the mapping between applications and port numbers at a specific time.

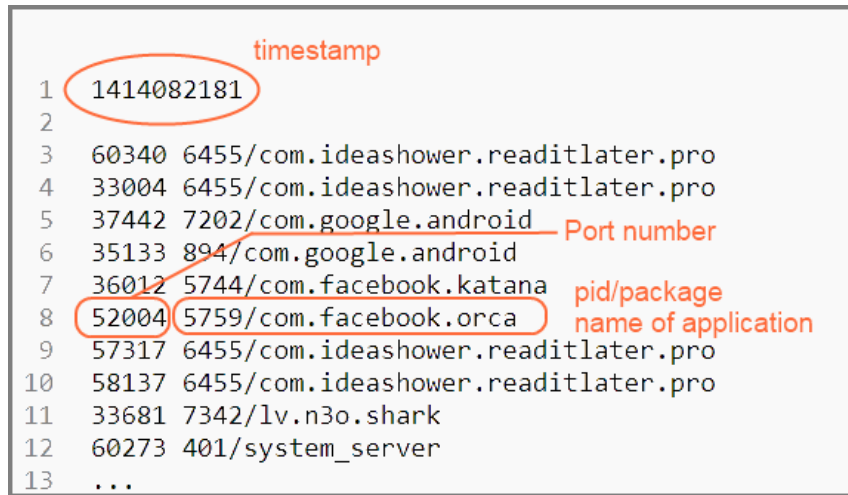
Since the packets are recorded for some duration of time and *netstat* gives the *port number vs. application* mapping for an instance of time (just when the command is executed), a single *netstat* output will not suffice. Therefore, we executed *netstat* periodically, while the packets were being recorded.

We used *ADB* [?] to communicate with the android device. To access the interactive shell of the device, *adb shell* was used. In our experiment, we connected the android device with a UNIX computer. Then we executed the shell script shown in Fig. 3.1 in the computer.

```
for i in {1..100}
do
    adb shell "
    su -c 'busybox netstat -pnt | grep tcp'
    " > netstat
    adb shell "date +%s" > netdump$i
    awk '{print $4 ":" $7}' netstat > netstattemp
    awk -F":" '{print $5 " " $6}' netstattemp>>netdump$i
    echo finished: $i
    sleep 1
done
```

Figure 3.1: Shell script used for netstat logging.

This script calls `netstat` 100 times, with 1 second interval in between. It filters just the necessary information (port numbers and corresponding pid/package names) from each `netstat` output, and saves them in separate files, along with the timestamp when the dump was taken. So after executing this script, we had 100 files (namely `netdump1`, `netdump2`, ... `netdump100`). A single `netdump` file is shown in Fig. 3.2.



```

1 1414082181
2
3 60340 6455/com.ideashower.readitlater.pro
4 33004 6455/com.ideashower.readitlater.pro
5 37442 7202/com.google.android
6 35133 894/com.google.android
7 36012 5744/com.facebook.katana
8 52004 5759/com.facebook.orca
9 57317 6455/com.ideashower.readitlater.pro
10 58137 6455/com.ideashower.readitlater.pro
11 33681 7342/lv.n3o.shark
12 60273 401/system_server
13 ...

```

Figure 3.2: A single `netdump` file

This step requires a rooted android device. Because, being a stripped down variant of linux, Android does not come with the `netstat` executable by default. So we used *Busybox*, a tool that allows execution of all standard UNIX commands in android. Busybox cannot be installed without super user permissions.

3.2.1.3 Extracting necessary information from packet dump

Packet dump (.pcap) contains comprehensive meta information about all packets, along with their contents. However, we are only interested in HTTP packets and

only three fields of each packet. Pcap filtering can be accomplished by many different ways among which we used Wireshark.

We opened the pcap file in Wireshark. Then the following display filter was applied on the dump:

```
http && ip.src == X.X.X.X
```

Here, X.X.X.X is the IP address of the device. This was used to filter out the http responses. For now, we are only interested in requests.

We kept only the following columns in Wireshark:

- Time (in Seconds since epoch format)
- Src Port
- Full Request URI

Then we exported the displayed packets summary in a plain text file. In our experiment, we named the file **filtered.txt** (shown in Fig. 3.3).

	Timestamp	Port #	URL
1	1414082186.261850	57001	http://www.quora.com/api/do_action_POST
2	1414082186.531015	47612	http://www.quora.com/
3	1414082187.769571	47614	http://qsc.is.quoracdn.net/-28ce1f6c6095d6c5.css
4	1414082187.770059	47615	http://qsc.is.quoracdn.net/-aeaeaa065aef57c7.js
5	1414082192.439645	47621	http://qph.is.quoracdn.net/main-thumb-t-4052-50-khhbtngfzevs...
6	1414082240.246866	45830	http://api.duolingo.com/api/1/version_info
7	1414082240.286386	54574	http://api.duolingo.com/api/1/store/get_inventory
8	1414082240.287393	55690	http://api.duolingo.com/api/1/store/get_inventory
9	1414082277.182687	47634	http://www.memrise.com/api/auth/facebook/
10	1414082279.105752	47635	http://www.memrise.com/api/app/settings/
11	1414082279.671243	47636	http://www.memrise.com/api/level/get/?with_content=true&lev...
12	1414082280.704813	47637	http://www.memrise.com/api/user/courses_learning/?user%5Fid...
13	1414082284.491800	47275	http://static.memrise.com/uploads/things/audio/14218347_136...
14	1414082284.491922	47276	http://static.memrise.com/uploads/things/audio/14218346_136...
15	1414082298.626474	54348	http://ajax.googleapis.com/ajax/libs/jquery/1.10.2/jquery.min.js
16	1414082302.333963	39488	http://data.flurry.com/aap.do
17	...		

Figure 3.3: Extracted information from the packet dump in **filtered.txt** file

3.2.1.4 Aggregating packet dump and netstat logs

Before this step, we had 100 files containing netstat outputs (*port-application* mapping at specific times). And we had a file `filtered.txt`, which contains the *port-URL* mapping for all HTTP request packets. We have written a script which processes all these files to produce the final App-URL table.

Since netdump files contains *port-app* mappings for specific moments (1 second apart), a packet's time will not necessarily match exactly with any of these moments. To assign such a packet to an application, we have made some assumptions.

Let t be the timestamp of a packet. Let $t_1, t_2, t_3, \dots, t_{100}$ are the timestamps of the netstat outputs (they are stored in corresponding netdump files). Of course $t_1 < t_2 < t_3 < \dots < t_{100}$. If $t < t_1$ or $t > t_{100}$, we discard the packet. We only consider packets with t such that $t_1 \leq t \leq t_{100}$.

Now for each of these packets, there is an i such that $t_i \leq t$ and $t_{i+1} > t$. We assign a packet to an application using the following rules:

1. If the same application A was using the packet's port at both t_i and t_{i+1} , then application A is the sender of the packet.
2. If application A was using the port at t_i , and the port was not in use at t_{i+1} , application A originated the packet.
3. If the port was not in use at t_i , and application A was holding it at t_{i+1} , application A originated the packet.
4. If the port was being used by application A at t_i and application B at t_{i+1} then,
if $t - t_i \leq t_{i+1} - t$, application A originated the packet. Otherwise application B originated it.

5. If no application was using the port at either t_i or t_{i+1} , We discard the packet.

Case 5 indicates that after t_i , some application opened the port, sent some packet(s) and then released the port before t_{i+1} . So this packet has gone untraced. We can lessen the frequency of such occurrences by decreasing the interval between t_i and t_{i+1} .

So for every packet (except the ones of case 5), we know the app which originated it. And `filtered.txt` contains full request URI of all packets. So we now know the URL specified in the packet was contacted by this application. We have logged these (Application, URL) entries for each packet and the App-URL table is ready. A sample table is shown in Fig. 3.4.

	Timestamp	Port#	App identifier	URL
1	1.414082194006204E9	52791	com.quora.android	http://www.quora.com/ajax/action_log_POST
2	1.414082195716379E9	42998	com.quora.android	http://www.quora.com/webnode2/server_call_POST
3	1.414082196603555E9	47619	com.quora.android	http://qph.is.quoracdn.net/main-thumb-9715372-5...
4	1.414082201279886E9	52225	com.quora.android	http://www.quora.com/webnode2/server_call_POST
5	1.414082240246866E9	45830	com.duolingo	http://api.duolingo.com/api/1/version_info
6	1.414082240286386E9	54574	com.duolingo	http://api.duolingo.com/api/1/store/get_invento...
7	1.414082255987588E9	45830	com.duolingo	http://api.duolingo.com/api/1/users/show?userna...
8	1.414082256455972E9	59259	com.duolingo	http://api.duolingo.com/api/1/store/get_invento...
9	1.414082269802286E9	39860	com.memrise.android	http://data.flurry.com/aap.do
10	...			

Figure 3.4: Final output: App vs. URL table

3.2.2 Matching the URLs with Domain-blacklists

When the App-URL table is ready, the table can be sent to a central server. The server can search the table for already known malicious domains, and notify the android device of any rogue application which might be trying to connect to a black-listed domain. The server can also enhance its blacklist by adding new domains that are contacted by a malicious application.

3.3 Results

We analyzed two known malwares using this method: *DroidKungFu* and *Anserver-Bot*, both known for contacting remote C&C servers [?]. Within minutes of installation *DroidKungFu* accessed *www.waps.cn*, which was listed as a malicious domain in *virustotal.com*. *Anserverbot* did not contact any blacklisted domain within the first 10 minutes when we recorded packets. The reason might be using an unreliable and freely available domain-blacklist from the internet. Or worse, maybe it communicates over protocol(s) other than HTTP.

Chapter 4

System call based detection

In this chapter, we will discuss the overall strategy of our second approach for malware detection, which uses system call [explanation] traces of applications to predict malicious activity. Following chapters will discuss the implementation details of this model and also the results achieved in our experiment using this model.

The central idea is to run an application for a specific amount of time (in our simulation - 10 seconds). During its execution, the details about the system calls it make to the operating system are recorded. We developed a machine learning model/classifier that can detect malware based on its system call trace. The syscall records of known malwares and known non-malwares are used to train the classifier. There will be two phases: training and classification. How the known malware and non-malware traces will be used to train the classifier is described in section 4.1. Section 4.2 describes how the model will classify an unknown app using its syscall trace.

4.1 Training

We will use a set of applications consisting both known malwares and known non-malwares as the training dataset. We will collect system call traces of all applications

of the training dataset (all of the applications will be run for a specific amount of time). The system call trace of a single application is a list of system calls the application used during execution. For example: **{recv, semget, msgget, ...}**; where **recv**, **semget**, **msgget** are system calls.

After collecting system call traces, We aggregate this traces to create two binary relation matrices M_{mal} and M_{nmal} . M_{mal} shows relation between system calls and malware applications, Where M_{nmal} shows relationship between system calls and non-malwares. M_{mal} and M_{nmal} matrices are defined as follows:

$$M_{mal}(i, j) = \begin{cases} 1 & \text{if } i^{th} \text{ malware uses } j^{th} \text{ syscall} \\ 0 & \text{otherwise} \end{cases}$$

$$M_{nmal}(i, j) = \begin{cases} 1 & \text{if } i^{th} \text{ non-malware uses } j^{th} \text{ syscall} \\ 0 & \text{otherwise} \end{cases}$$

Then we calculate the Goodness Rating of j^{th} syscall, G_j as follows,

$$G_j = \frac{1}{N_{nmal}} \sum_{i=1}^{N_{nmal}} M_{nmal}(i, j) - \frac{1}{N_{mal}} \sum_{i=1}^{N_{mal}} M_{mal}(i, j)$$

where N_{nmal} and N_{mal} are number of non-malware and malware samples.

4.2 Classification

To classify an unknown application as *malware* or *non-malware*, first, we execute the application for the same time duration we used with each training application. We collect the system call trace of that application during that execution, same as before. But this time, we also record the frequency of each syscall used by

the application during execution. So now, the syscall trace of an application during classification phase can be expressed as a list of pairs of syscalls and their frequencies. For example: $\{(\mathbf{recv}, 1032), (\mathbf{semget}, 143), \dots\}$ is a trace of an application which called the **recv** routine 1032 times, **semget** 143 times and so on.

Then we define the Goodness Rating of that application as follows

$$G_{app} = \sum_{s \in S_{app}} G_s \times F_s$$

Where, S_{app} is the set of system calls used by *app* and F_s is the frequency of syscall s in *app*.

If we assume that malwares uses similar system calls which are distinctive from those used by non-malwares; It is logical to assume that a malware will use more syscalls those has lower goodness ratings and less syscalls having higher goodness ratings. The opposite can be said for non-malware applications. So this will result in higher goodness ratings of non-malware applications and lower goodness rating for malware applications.

Now for classification, we check if the goodness rating of the application under inspection exceeds some threshold. If so, we classify it as non-malware. otherwise we flag it as malware.

$$\begin{cases} \text{app is a malware} & \text{if } G_{app} > T \\ \text{app is not a malware} & \text{otherwise} \end{cases}$$

Where, T is a threshold. Theoretically, the threshold should be zero. But it actually depends on the experiment and the training data used. We will

Chapter 5

Experiment on System call based classifier

In this chapter, we will go into details on the experiment we conducted to validate our model. The linklink.

5.1 Preparing Simulation

We collected system call traces of all applications using a single device. The reason behind this is we intended to provide identical environments for all applications to execute in. The device was reset to factory default configuration and the device needed to be *rooted* [explanation]. We used standard linux utility *strace* [explanation] to trace system call of applications. We also used *timeout* [explanation] command to run every application for a fixed duration of time. Although *strace* and *timeout* are standard linux utilities, they are not included in standard Android builds. So we had to collect the source code of this tools and cross-compile them for the architecture of the device on which the simulation is run. The compilation task requires *Android NDK* [explanation]. After the binaries are created for our desired CPU architecture (in our case **ARMv7**), they are put in the **/system/xbin** of our device, so that they can be accessed by a shell script run through *adb* [explanation]. Copying any binary into **/system** requires superuser permission, that is one of the reasons why we needed to *root* our device at the first place.

5.2 Simulation

We planned to collect system call traces of a total of 453 malwares and 227 non-malwares. We wrote a batch script that automates the whole process. The script executes commands in the device using *adb* [explanation]. The workflow of the script is outlined in Algorithm 1.

Algorithm 1 Syscall trace collect script

```
1: procedure COLLECT-ALL-SYSCALL-TRACE(directory)
2:   for each apk file [explanation] in directory do
3:     pckgname  $\leftarrow$  get package name from that apk using aapt[explanation]
4:     Install the apk in the device.
5:     Launch the app
6:     pid  $\leftarrow$  ps(pckgname)
7:     stracelogs[pckgname]  $\leftarrow$  output of strace(pid) with 20 seconds timeout
8:     Force close the app
9:     Uninstall the app
10:  end for
11:  return stracelogs
12: end procedure
```

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Appendix A

Acronyms

AH	Authentication Header
AR	Access Router
AZS	Anchor Zone Server
BA	Binding Acknowledgement
BSP	Basic Support Protocol
BU	Binding Update
CGA	Cryptographically Generated Address
CN	Correspondent Node
CoA	Care of Address
CoT	Care-of Test
CoTI	Care-of Test Init
DDoS	Distributed Denial of Service
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
DoS	Denial of Service
ESP	Encapsulating Security Payload
FTP	File Transfer Protocol
HA	Home Agent
HiSIGMA	Hierarchical SIGMA

HIP Host Identification Protocol
HMIPv6 Hierarchical Mobile IP version 6
HoA Home Address
HoT Home Test
HoTI Home Test Init
HZS Home Zone Server
ICMP Internet Control Message Protocol
IETF Internet Engineering Task Force
IKE Internet Key Exchange
IP Internet Protocol
IPsec IP security
LCoA Local Care of Address
LFN Local Fixed Node
LLM Local Location Manager
LM Location Manager
LMA Local Mobility Anchor
MAP Mobility Anchor Point
MH Mobile Host
MIP Mobile IP
MIPv6 Mobile IP version 6
MITM Man In The Middle
MNN Mobile Network Node
MNP Mobile Network Prefix
MR Mobile Router
MSF Mobility Scalability Factor
NEMO Network Mobility
NRT Non-Real Time
PDA Personal Digital Assistant

RA Router Advertisement
RBU Refreshing Binding Update
RCoA Regional Care of Address
RR Return Routability
RT Real Time
RTT Round Trip Time
SA Security Association
SCTP Stream Control Transport Protocol
SIGMA Seamless IP-diversity based Generalized Mobility Architecture
SINEMO Seamless IP-diversity based Network Mobility
SPI Security Parameters Index
TCP Transmission Control Protocol
TNRL Telecommunications and Networks Research Lab
UDP User Datagram Protocol
VMN Visiting Mobile Node