Hey, you, keep away from my device: remotely implanting a virus expeller to defeat Mirai on IoT devices

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June, 2017
PSU-S2-TR-2017-04001

Abstract
Mirai is botnet which targets out-of-date Internet-of-Things (IoT) devices. The disruptive Distributed Denial of Service (DDoS) attack last year has hit major Internet companies, causing intermittent service for millions of Internet users. Since the affected devices typically do not support firmware update, it becomes challenging to expel these vulnerable devices in the wild.

Both industry and academia have made great efforts in amending the situation. However, none of these efforts is simple to deploy, and at the same time effective in solving the problem. In this work, we design a collaborative defense strategy to tackle Mirai. Our key idea is to take advantage of human involvement in the least aggressive way. In particular, at a negotiated time slot, a customer is required to reboot the compromised device, then a “white” Mirai operated by the manufacture breaks into the clean-state IoT devices immediately. The “white” Mirai expels other malicious Mirai variants, blocks vulnerable ports, and keeps a heart-beat connection with the server operated by the manufacturer. Once the heart-beat is lost, the server re-implants the “white” Mirai instantly. We have implemented a full prototype of the designed system, and the results show that our system can evade Mirai attacks effectively.

Keywords: Mirai, Botnet, IoT
1 Introduction

In October 21st, 2016, Dyn, an infrastructure vendor, which serves Internet’s top giants, such as Netflix and Twitter, was attacked by the record Distributed Denial of Service (DDoS) attack [2]. The attack was later found originated from a botnet malware – Mirai. It was the same botnet malware that attacked an security researcher’s blog website and had the record 620 Gpbs stream in September 21st [5]. The Mirai malware mainly targets digital video recorders (DVRs) and IP cameras, which are mainly old and low-end products which have no firmware update capability. In addition, since the firmware is read only, the Mirai code can only stay in the DRAM of the device; rebooting the device also wipes the Mirai code. That being said, once infected, the only recourse is to wait for these devices to be rebooted since there is no path to remediation through any type of reconfiguration. Given the large amount of these vulnerable devices, and the fact that there is no way patch them, Mirai based attacks have become a time bomb which no one can defuse.

Under the pressure from media, some manufacturers claimed they were to recall vulnerable products linked to this massive DDoS attack. For example, Hangzhou Xiongmai Technology planned to recall 4.3 million Internet-connected camera products from the U.S market [1]. Although the company invests a huge time and energy to amend the situation, it only mitigates later attacks, simply because device users have no incentive to cooperate in the recall process. They are not willing to spend time on packing these devices and sending them back, because the Mirai malware does not affect the normal operations of the compromised devices. As a result, there are still a lot of vulnerable devices remaining in the wild.

When passive recalling turned out to be inefficient, the manufacturer could also actively contact customers to perform remote diagnose. If the device is found compromised, the customer agent could explain the consequence of leaving the device in the wild, and urge the customer to replace the device for free. However, a manufacturer may have millions of products sold around the world [1]. It is not practical for the customer service to contact each user to fix the problem.

Academia is also active in solving the Mirai problem. In [17], the authors propose a fancy idea to deploy a “white” Mirai-like system. The government is required to record vulnerable products and push the related manufacturers to fix the problem. This solution inherits a bunch of code from Mirai. Notably, like the malicious Mirai, the “white” Mirai actively scans neighbour vulnerable devices, and infects them. The infected devices then become immune to any other similar attack, as a result of blocked ports. As the “white” Mirai spread itself through infection, it exhausts resources and imposes heavy overhead for the resource-constraint devices. Furthermore, there is a combat between the “white” and real Mirai. Only the winner takes control of the device. In fact, Mirai has already infected millions of devices which has a good chance to win the game. In this sense, the solution is non-deterministic. Last but not least, the solution has legal concerns. Although this Mirai-like system is conducted by the government, it is still illegal to compromise a device without the consent of the user or the manufacturer.

In summary, both industry and academia have no solution that is simple to deploy, and at the same time effective in addressing the problem.

In this paper, we propose a solution which defeats Mirai effectively and avoids aforementioned issues. The key idea of our solution is to take advantage of human involvement in the least aggressive way. The idea of kicking in human is based on the observation that rebooting the device also wipes the Mirai code in memory. Based on this observation, we propose a collaborative defense strategy to tackle Internet-of-Things (IoT) device based DDoS attacks. At a high-level, our solution resembles the “white” Mirai work in that both utilize attacker’s method as a defense measure for tit for tat. However, we require the customer to collaborate with the manufacture by rebooting the device at
Table 1: Comparison of different solutions

|                      | Simplicity | Effectiveness | Manageableness |
|----------------------|------------|---------------|----------------|
| Recall               | ×          | ✓             | ✓              |
| Customer Service     | ×          | ✓             |                |
| White Mirai          | ✓          | ×             | ×              |
| Our solution         | ✓          | ✓             | ✓              |

the negotiated time slot. At this time slot, the malicious Mirai has very little chance to kick in, while the “white” Mirai could “break” into the device in time. In particular, the manufacturer builds an implanter server which remotely implants a virus expeller into a vulnerable device to expel other Mirai away from it. Once implanted into a device, the virus expeller closes all the ports used by malicious Mirai, leaving no room for Mirai to access this specific device. The implanter server operated by the manufacturer is responsible for finding the vulnerable devices, implanting the virus expeller and keeping the virus expeller alive in a specific device.

Table 1 compares our solution with three aforementioned solutions. In the table, simplicity means there is no much burden for the customers and the manufacture to carry on the emendation. Effectiveness means the solution can effectively defeat Mirai. Manageableness means the manufacturer can keep track of the deployment of the system.

In summary, we make three main contributions in this paper:

1. We analyze the architecture of a legacy digital video recorder which is subject to the Mirai attack.
2. We propose a practical solution to defeat Mirai the botnet malware, which is simple, effective and manageable.
3. We implement a proof-of-concept prototype and show that it can successfully shield vulnerable devices from Mirai’s infection.

Roadmap. The rest of the paper is organized as follows. Section 2 reviews related work about botnet, and security problems associated with the emerging IoT device. Then, in Section 3, we present the architecture of the Mirai botnet, as well as a typical vulnerable device involved in the Mirai attacks. Section 4 summaries key features of the Mirai botnet. The design and implementation are the proposed solution are demonstrated in Section 5 and Section 6 respectively. Then we evaluate the effectiveness of the system in Section 7, followed by some discussions about the limitation the work. Finally, Section 9 concludes the paper.

2 Related Work

2.1 IoT Security

The Internet of Things are emerging nowadays. However, under the pressure of the time-to-market, manufacturers of these IoT devices pay little attention to the security and privacy enhancement for their products. This kind of neglect results in serious hazards and attacks [7, 11, 12, 22, 23, 14]. To tackle these problems, more and more security researchers in academia and industry focus on IoT security.
Pa et al. [21] analyzes the increasing threats against IoT devices and show that Telnet-based attacks that target IoT device have increased since 2014. It proposes IoT honeypot and sandbox on different CPU architectures to analyze the malware samples targeting Telnet-enabled IoT devices. Fernandes et al. [15] provides the first depth of security analysis on the smart home programming platform, i.e. Samsung-owned SmartThings, and discovers the over-privilege problem. This problem can make a malicious battery monitor SmartApp subscribe door lock PIN change event. To solve this problem, Jia et al. [18] propose a context-based permission system for appified IoT platforms that helps users perform effective access control. Costin et al. [13] performs a large-scale analysis of firmware images and discovered 38 previously unknown vulnerabilities in over 693 firmware images. For example, some devices’ firmware images hardcodes credentials. Fernandes et al. [16] present FlowFence, using information flow approach within application structure to prevent application misusing sensitive data in IoT devices. In our work, we target to defeat Mirai in a simple, effective and manageable way. It helps manufacturers build an implanter server to implant the virus expeller into vulnerable devices to immune Mirai’s infection and eventually stop Mirai botnet’s attack.

### 2.2 Botnet

Botnet has been the research topic since 2000s. It can bring significant damages to the security of both individuals and businesses. To counter botnet, there are usually two effective ways comprised of preventing botnet’s spreading and prevent botnet’s attack. Prevent botnet’s spreading often needs the victim devices’ users or administrators to fix their devices’ vulnerabilities. Without the capability of exploiting a specific vulnerability, the botnet cannot increase its size. This results in the reduction of this botnet’s attack power.

There are tow most common strategies to prevent botnet’s attack. They are disabling C&C servers and sinkholing the attack traffic [10, 19, 20]. Taking down C&C servers can defeat the botnet, but just in a while. Because botnet attacker can change C&C servers periodically. Besides, if the server are not in the scope of local law enforcement, it is not easy to do this. This way also has a defect that even if C&C servers are taken down, the botnet’s zombies are still active in the wild which can be reused later by others. Sinkholing the attack traffic happens when one botnet is attacking a specific victim. It requires the cooperation of upstream Internet service providers, such as ISP. It also needs to identify the unique signature of this traffic to be filtered. Our work defeat Mirai by preventing its spreading by implanting the virus implanter into the device. In this way, Mirai cannot infect this specific device and its size cannot increase.

### 3 Explaining Mirai

This section details Mirai’s design, which is helpful in understanding the proposed defense mechanism. To begin with, we introduce a Mirai-vulnerable device.

#### 3.1 Mirai-vulnerable Device

IoT devices subject to Mirai attacks are mainly IP Cameras and Digital Video Recorders (DVR). These emerging devices are usually fragile and vulnerable, because very few security measure is built into the system. To make things worse, many of these IoT devices run naked in the Internet – back-door accounts can be used to remotely access the device with root privilege. In this section,
we dissect a Dahua digital video recorder of model DH-3004, whose vulnerability statement is given at the end.

**Hardware.** This device has four BNC connector for video input, and two for audio input. It also has two USB ports for connecting peripheral like flash disks and a mouse. An Ethernet port is used to connect to the Internet and a VGA port is used to connect a monitor. The device is powered by an ARM ARM926EJ-S processor, with 43 MB of RAM. In addition, a hard disk can be plugged in a SATA interface to record captured signals.

**Software.** The device runs *HiLinux*, a tailored Linux distribution, integrated with BusyBox as its toolset. The kernel is a legacy one of version 2.6.24. By default, six TCP ports are open. They are 23, 80, 101, 102, 554, and 6623. Some of them are used to telnet into the system for diagnosis, while others are used to connect a mobile app for remote control of the device. The system has a root account with no password. Since the flash of the system is read-only, there is no way to set up a new root password.

**Vulnerability Statement.** DH-3004 device has at least two ways for remote access, including telnet and HTTP. Any one who can reach DH-3004 can login into the device with root privilege through telnet access. As there is no way to set a root password, and firmware cannot be updated, the device is highly vulnerable to Mirai attacks.

### 3.2 Mirai Analyses

As a botnet malware, Mirai uses the client-server (CS) model to connect the bot with a command and control (C&C) server. However, compared with traditional botnet malwares, Mirai is special in the infection phase. Instead of infecting directly through the bots, Mirai botnet is only used to scan and collect vulnerable devices and the server launches the actual attack to implant botnets.

There are three modules in Mirai, a *Bot* module, a *ScanListen* module, and a *Load* module. Figure 1 illustrates Mirai’s architecture, and the information flow and the relationship among these modules. The Bot is a program running in victim devices. It scans other devices on the Internet having the same vulnerability. If it finds one, the vulnerable device’s information will be uploaded to the ScanListen module, which runs in a pre-known server. The information includes login credentials, device IP address and vulnerable ports, etc. After receiving the these information, the ScanListen module sends it to the Load module, which runs in the same server. The Load module then use these information to infect the target device and implant Bot.

**The Bot Module.** This is the attack module which perform DDoS the actual attacks to the
victim server. It is also used to scan the Internet to collect other vulnerable devices, and collect their information. The Bot module implements features and functions listed below.

1. **Preventing the device from rebooting.** Mirai’s bot only exits in the memory. If the device reboots, bot disappears. Therefore, in order to prevent this from happening, bot writes the request command “0x80045704” to the “watchdog” of the device to disable rebooting in face of a system hang up.

2. **Process hiding.** Mirai uses a random string to hide its process name.

3. **Preventing second infection.** The Bot module opens the port 48101 and binds to this port. If another bot wants to bind this port, it would detect this event. In this way, mirai ensures there is only one bot running on the target device.

4. **Blocking ports.** Mirai closes port 23(telnet), 22(ssh), 80(http) to block other botnet malware’s attack.

5. **Experlling other malwares.** Mirai’s bot module scans the system to find the fingerprint of other malwares. With root privilege, Mirao is able kill other malware processes.

6. **Device Scan.** Mirai bot periodically, scans neighboring devices to discover vulnerable ones. However, it excludes those device whose IP addresses belong to the General Electric Company, Hewlett-Packard Company, US Postal Service, etc. as depicted in listing 1. If a vulnerable device is found, the bot module sends back this device’s information to the ScanListen module. Bot uses brute-force to scan other devices. Namely, Bot hard-codes 62 pairs of back-doored user name and password pair. Listing 2 lists the revealed username-password list. These string is further obfuscated by a simple xor operation by “0xDEADBEEF”.

7. **DDoS Attack.** The bots connect to the C&C server and wait for the command to attack the target server.

| Listing 1: IP filter in bot |
|----------------------------|
| 1...                     |
| 2 while (o1 == 127 ||    |
|   127.0.0.0/8            |
|   - Loopback             |
| 3 (o1 == 0) ||           |
|   0.0.0.0/8              |
|   - Invalid address space|
| 4 (o1 == 3) ||           |
|   3.0.0.0/8              |
|   - General Electric Company|
| 5 (o1 == 15 || o1 == 16) ||
|   15.0.0.0/7             |
|   - Hewlett-Packard Company|
| 6 (o1 == 56) ||           |
|   56.0.0.0/8             |
|   - US Postal Service    |
| 7 (o1 == 10) ||           |
|   10.0.0.0/8              |
|   - Internal network      |
| 8 (o1 == 192 && o2 == 168) ||
|   192.168.0.0/16         |
|   - Internal network      |
| 9 (o1 == 172 && o2 >= 16 && o2 < 32) ||
|   172.16.0.0/14          |
|   - Internal network      |
Listing 2: Hardcoded usernames and passwords in bot

```c
// Set up passwords
add_auth_entry ("\x50\x4D\x4D\x56", "\x5A\x41\x11\x17\x13\x13", 10); // root xc3511
add_auth_entry ("\x50\x4D\x4D\x56", "\x54\x4B\x58\x5A\x54", 9); // root vizxv
add_auth_entry ("\x50\x4D\x4D\x56", "\x43\x46\x4F\x4B\x4C", 8); // root admin
add_auth_entry ("\x43\x46\x4F\x4B\x4C", "\x43\x46\x4F\x4B\x4C", 7); // admin admin
add_auth_entry ("\x50\x4D\x4D\x56", "\x5A\x4F\x4A\x46\x4B\x52\x41", 5); // root xmhdipc
add_auth_entry ("\x50\x4D\x4D\x56", "\x46\x47\x44\x43\x57\x4E\x56", 5); // root default
add_auth_entry ("\x50\x4D\x4D\x56", ",", 4); // root (none)
```

The ScanListen Module. This module is responsible for sending the information collected by the bots to the Load module. The format is “IP-Address:Port” and “User-Name:Password”.

The Load Module. This module gets the input from ScanListen and performs attack against each vulnerable devices. The critical steps are as following.

1. Login to the target device through exposed vulnerabilities.
2. Make sure the target device has BusyBox installed.
3. Find a read-writable directory.
4. Copy “/bin/echo” to the read-writable directory.
5. Implant bot through “echo”, “wget” or “tftp” commands by connecting a server.
6. Execute the bot program in memory.
7. Delete the bot program in the file system.
4 Dissection of Mirai

This section dissects Mirai, lists some key features in the spread of Mirai, and argues some assumptions regarding the capabilities of customers.

Mirai is widely deployed in the wild and there are thousands of Mirai bots on the Internet scanning other vulnerable devices. The devices infected by Mirai have no way to update firmware. In addition, most of them operate on a temporary in-memory file system, which loses its contents after power off. By keeping track of each sold device, the device manufacturer can contact its customers, e.g., by the email. The customer may not a power user, who has advanced computer skills. We assume the customer is only capable of following the product manual to configure the device and power on/off the device.

Although Mirai has an effective way to scan devices, the IP addresses are random chosen. There should be a time window when the device is in clean state after rebooting.

The way Mirai deploys the botnet is straightforward. It first remotely exploits the weak-password vulnerability, then implants the bot and waits for the command to attack the target server. In this process, once implanted into a device, the bot closes several ports to disable remote access to the device originated other malware. The bot also deletes the malicious executable binary on the file system to conceal its presence.

From the aforementioned analyses on Mirai botnet, we figure out two key factors in the infection of Mirai. They are the remote access and the hard-coded password vulnerability. Therefore, in order to defeat Mirai, there are two effective ways, including fixing the password vulnerability and closing the ports for remote access. As the device’s firmware cannot be updated, the password vulnerability cannot be fixed permanently. In addition, the device may not support changing password even temporarily. On the other hand, although closing the ports for remote access cannot persist either, through collaboration between the customer and manufacture, it is possible to minimum the time of vulnerable devices with open ports exposed on the Internet.

5 Design

The key idea of our solution is to use a “tit for tat” strategy to defeat Mirai. That is, the manufacturer deploys a Mirai-like botnet system to implant virus expeller into the vulnerable devices and close the ports for remote access to defeat Mirai automatically. Before illustrating the system, we first discuss the challenges which can help understand the system design.

5.1 Challenges

The basic idea of our solution is also implanting a “white” Mirai to the vulnerable device. The first challenge is how to control the infection range and the influence on the normal operations of the devices. From the analysis above, Mirai uses bots to scan other devices and implants bots into the vulnerable devices through the Load module automatically. When deploying the Mirai-like system, we should consider the overhead that can bring to the Internet and the devices. For example, these IP camera and DVR devices are usually resource-constrained. Exhausting device’s resource to defeat Mirai is not acceptable for the customers. Besides, if a manufacturer scans the Internet to discover the vulnerable devices of its own, this kind of spam stream may block some network streams. Therefore, how to control the Mirai-like system to make it effective and bring minimum influence on the Internet is very important.
The second challenge is how to ensure our “white” Mirai to be implanted into the target device effectively. In section 4, we assume Mirai has been widely deployed in the wild and there are thousands of bots to find the vulnerable devices. In fact, the botnet deployed by the attacker is very large [6]. Mirai uses bot to scan the devices, so the larger the botnet is, the faster Mirai can infect a new device. If the implanting of the manufacturer is not as efficient as the wild Mirai, Mirai bot can infect a device earlier than ours. In this case, as the ports has been closed by Mirai’s bot, our “white” Mirai cannot be implanted at all.

5.2 System Architecture

Figure 2 depicts the system design of our “white” Mirai and its difference with the original Mirai. The gridded modules are those removed from the original Mirai. As our system derives from Mirai, we must remove the code and modules designed to perform DDoS attacks to prevent our benign system is abused. The gray modules are these newly added into the system. The two most important modules include a virus expeller and a implanter server, which run on the vulnerable device and the manufacture maintained server respectively.

The Virus Expeller. Once implanted into a vulnerable device, the virus expeller expels the infection of Mirai’s bot. The virus expeller inherits code from Mirai’s bot, but distinguishes itself from Mirai bot by removing the attack module and scan module. Besides, as depicted in figure 2, the virus expeller also adds several functions, such as fingerprint obtaining module and heart-beating module. Fingerprint obtaining module is responsible for collecting device’s information, such as its unique ID. This module is used to avoid the legal problem. In particular, if the virus expeller is injected into a vulnerable device which is produced by another manufacture, without acknowledgment from the customer, legal problems arise. Therefore, the fingerprint obtaining module can make sure the infected device belongs to the exact manufacturer.

The heart-beating module is a client program for the heartbeat service and reports aliveness to it in the implanter server periodically. More details about this heartbeat functionality will be described in section 5.2.

The virus expeller’s core part is a blocking module. It closes the ports for remote access as soon as it is implanted into a device. However, there is a time window between this virus expeller is executed and the ports are closed. This time window allows original Mirai to infect this specific
device. Thus, the blocking module kills Mirai’s bot process if one is found.

As Mirai-like system deploys virus expellers in the resource-constraint devices, the resource used in these devices should be restricted. Otherwise, the user may complain about this heavy-weighted protection method. Because the scan module in the original Mirai’s bot consumes a lot of resources, in order to limit the influence on the device, instead of performing scan on the device, we move this function to the implanter server. Another benefit of removing the scan function is to avoid generating much spam stream which has a bad influence on the Internet.

**The Implanter Server.** The implanter server runs five programs, including Load module, ScanListen module, Heartbeat module, Scan module, and HTTP module.

The scan module inherits code from Mirai’s scan module. It is used to scan the Internet to find the vulnerable devices. However, in order to implant the virus expeller only to the products of a specific manufacturer, the scan module keeps this specific manufacturer’s information. Furthermore, this module is extended and can scan an IP address range or a specific IP address to find vulnerable devices.

The load module and the scanlisten module have no difference with Mirai’s load and scanlisten modules. They are responsible for collecting the vulnerable devices’ information from the scan service and implanting the virus expeller into these devices. The load module is also used for downloading the executable payloads from a HTTP module on the server.

The heartbeat module monitors each virus expeller’s aliveness and re-implant them if some accident happens, such as devices’ unplanned power-on and power-off, as this would clear the virus expeller. There may be a concern in heartbeat service’s usage, i.e. whether these virus expellers may results in a DDoS attack for this implanter server. But according to the material exposed by Mirai’s authors [4], 2% CPU can support 400k bots. Therefore, this is not a problem.

### 5.3 Work Flow

The operation of our system has three phases, deployment phase, regular phase and negotiation phase. Figure 3 illustrates how three phases work together to defeat Mirai attacks.

**Deployment Phase.** In this phase, the manufacturer deploys the system by firstly running the scan service to find vulnerable devices and implant the virus expeller into them. This phase is a
basic phase which is simple and straightforward. Its effectiveness depends on how quickly the scan service can find vulnerable devices. In the real world, this phase may be optimistic. Because in our assumption, Mirai is already deployed in the wild and all the devices on the Internet may be infected by it. However, there should be some devices which are powered on and the time window is long enough for this scan service to find them and implant the virus expeller.

**Regular Phase.** The manufacturer is not involved in this phase. In this phase, the heartbeat client in the virus expeller sends back a heartbeat to the heartbeat service in the implanter server periodically. At the same time, the heart-beating service has a timer for each virus expeller and continuously checks them. If the timer exceeds a specific value, it means the related virus expeller loses connection with the server. In this way, the manufacturer can know whether a virus expeller has successfully ran on a specific device. If this device is accidentally rebooted, the manufacturer can know exactly which device’s virus expeller loses connection with the heartbeat service. Then the heartbeat service can invoke the scan service to scan a specific IP address range deduced from the specific device information obtained previously, and can re-implant the virus expeller into the device afterwards.

**Negotiation Phase.** In the last two phases, we implicitly assume that our Mirai-like system can implant the virus expeller into a target device. However, in practice, as discussed in section 5.1, Mirai botnet has a large number of bots and can already infect a target device. If Mirai bot has already been in a device, no virus expeller can be implanted into this device. Because Mirai bot firstly closes the ports for remote access, there is no other way to access this device. In order to handle this situation, the customer must collaborate with the manufacturer to clear Mirai and implant the virus expeller. In this phase, the customer and the manufacturer firstly agree on a specific time. At that time slot, the user uses a computer, to access a special web page operated by manufacturer, and then reboots the vulnerable device. The manufacturer can get a clue about the IP range this specific user’s device is in. As a result, the manufacturer can leverage the scan service to quickly scan the IP range to locate this vulnerable device and implant the virus expeller before Mirai can infect this device. As the Mirai botnet does not know the time negotiated by the customer and the manufacture, our solution can effectively block spread of original Mirai. Furthermore, according to the experiment done by [8], it costs around 98 seconds for Mirai botnet to infect a device after being connected to the Internet. So there is little chance for Mirai to infect this device at the very moment that the customer reboots the device.

With regard to the IP range, we may need to consider different circumstances in reality. If a device is in the private network and does not have a public IP address, it seems the Mirai-like system cannot infect this device directly. However, the same applies to Mirai. Moreover, some devices leverage UPnP (Universal Plug and Play) protocol to do NAT traversal and expose themselves on the Internet for user convenience. As a result, the Mirai botnet can directly connect to this device through the public IP address.

### 6 Implementation

Our implementation is based on the open-sourced Mirai code [9]. Mirai’s code base is more than 9K Lines Of Code (LOC), including C/C++, Go and Bourne Shell. As we remove attack modules from Mirai and add heartbeat client/server modules, etc., the code base of our implementation is about 6K LOC. In this section, we only describe the functions newly added into the virus expeller and the implanter server.
6.1 The Virus Expeller

Two functions are added into the virus expeller. They are the fingerprint obtaining module and the heart-beating module. The former gets system information from pseudo files, such as “/proc/cpuinfo”, “/proc/hiversion”, etc. These information is used to determine whether this device is the product of a specific manufacturer.

The heart-beating module is simple. It sends back a magic number “0xE84Eb1C8” to the heart-beat service every minute to report the virus expeller’s aliveness.

6.2 The Implanter Server

The implanter server has been added two more services, including a scan service and heartbeat service. The scan service inherits code from Mirai’s bot scan module. It is modified to scan a specific manufacturer’s products with specific username-password pairs. This can accelerate the scan speed and to some extent exclude other manufacturer’s products. Furthermore, in the original Mirai’s bot, the scan module only get random IP addresses to scan. In ours, we only need to scan a specific IP range obtained from the load module.

The heartbeat module is the server process for the heartbeat client in the virus expeller. It records each virus expeller’s IP address, refreshes the timer for each virus expeller, and checks the timer periodically. In our design, the heart-beating module checks the timer to see whether it exceeds 70 seconds. If a timer exceeds the time limit, this module will invoke the scan service to scan that specific IP address and the related IP address range to relocate this device, in case it is accidentally rebooted.

7 Evaluation

We evaluate the functionality of the proposed Mirai-like system using the device mentioned in section 3.1. The implanter server runs in a Debian 8 Linux operating system which is powered by an Intel i7-4790 processors with 2GB memory.

We are interested in three functions. The first is whether the proposed system can implant the virus expeller into a target device through this process: Scan → ScanListen → Load → Web → Virus Expeller (in the target device) → Heartbeat. If the virus expeller is implanted into a device, the heartbeat service can receive the messages sent by it. Using wireshark running on a PC which monitors the network packages, we measured the time taken to implant the virus expeller since the scan service starts to scan this device. On average, it takes about 10 seconds, which is much faster than the wild Mirai does. After that, the heartbeat can periodically receive a message sent from the virus expeller which shows that this system works.

The second is whether the virus expeller can defeat Mirai’s infection once being implanted into a device. We run this experiment by implanting the virus expeller into this target device firstly and then run the scan service to scan this specific device to find whether the load service can receive any information. As our scan service, scanlisten service and load service inherit code from Mirai, if our Mirai-like system can scan the device and return related information to the scanlisten service, this means the target device can be infected by Mirai even there is a virus expeller inside. From load service’s log message, we can directly find the virus expeller is implanted into this device and no more message is generated after that. Besides, we try to use telnet to connect to this device and fail to connect into this device. Therefore, once being implanted into a device, the virus expeller can succeed in defeating Mirai by closing related remote access ports.
The third is whether the implanter server can re-implant the virus expeller into this specific device, if the device is accidentally rebooted. We run this experiment by rebooting the device and monitor the log of the heartbeat service. From the log, we can see a list of operations. First, the virus expeller stops sending back the aliveness message. Second, the heartbeat service invokes scan service to scan the target IP address range. Third, the scan service finds the target device and the virus expeller is implanted by the load service.

8 Discussion

8.1 Limitation of the Present Work

The proposed work implants a virus expeller into a target device to defeat the Mirai botnet malware. Our system includes three phases, i.e. deployment phase, regular phase and negotiation phase. The deployment phase is a basic phase which leverage the scan service to find vulnerable devices in the Internet and the load service to implant the virus expeller. The regular phase is based on the heartbeat module and scans service to keep the virus expeller implanted in the device. These two phases potentially assume the Mirai-like system can implant the virus expeller into the target device. But in the wild, there may be few devices left intact which result in the efficiency of these two phases. The negotiation phase involves the device’s user, which introduces determinacy into the system. However, the user may not be cooperative, which limits the efficiency of our system.

The proposed work only defeats the original Mirai botnet malware for now. This malware’s variants may use different ports or use different vulnerabilities to infect the target devices. For different ports, this system can add them into the virus expeller’s port list which is easy to deploy. For new vulnerabilities, our system can also defend the infection by closing the specific ports used in these vulnerabilities. However, a port closed by the virus expeller may be a functional port used by the device. When it is closed, the device’s function is influenced. For example, port 80 is used by the DH-3004 device to show the web interface. If it is closed, the user can no longer access it.

With regards to the potential threat to the different participants, such as the user, the manufacturer, the ISP, etc., the only concern is the influence on the Internet and the device. As the attack module has been remove from Mirai, our system cannot be abused. Besides, this system has removed the scan module from the virus expeller. However, despite of the above mitigation, there may still exist some influences on the Internet and the device.

There are also legal concerns related with the present work [3]. Although our system limit the infection devices within this specific manufacturer’s products, the way it uses is still not decent. Furthermore, different countries may have different laws to justify this behavior. Thus, our system only works if the appropriate legal framework is in place to allow this behavior.

8.2 Future Work

The present work solves the problem that the Mirai botnet malware exploits the weak password vulnerability in IoT devices to deploy botnet and perform DDoS attacks. It leverages Mirai’s code base and implants the virus expeller into a target device to defeat Mirai. At present, our system only works only if the target device is clean, i.e. Mirai has been cleared by rebooting or this device has not been infected by Mirai at that time. In the future, we will assume that the device has already been infected by Mirai. One potential solution is to discover Mirai’s vulnerability and exploit this vulnerability to disarm Mirai.
9 Conclusion

We have presented a new mechanism to aid manufacture in amending the Mirai-vulnerable devices in the market. Different from recalling or customer services, in which customers are unwilling to cooperate, our solution needs minimal involvement of customers. Different from the “white” Mirai proposed in [17], our solution does not need brute-force scan to infect others, and can deterministically patch the compromised device.

A proof-of-concept prototype has been implemented. Experimental results show that the proposed solution is both simple and effective. Given the great number of Mirai-vulnerable devices in the wild, our solution provides an attractive path towards mitigating the threats from Mirai, until all the vulnerable devices are retired. Since our solution requires close cooperation with the manufactures, we plan to contact the involved manufactures to further carry out our solution in real world.

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