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New Variants of Mirai and Analysis

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Synonyms

Botnet; DDoS; IoT; Malware

Definition

Mirai, which means "the future" in Japanese, is a self-propagating malware that infects vulnerable networked IoT devices so as to turn them into part of a botnet that can be leveraged to perform large-scale distributed denial-of-dervice (DDoS) attacks.

Historical Background

The Mirai botnet was first discovered in August 2016 (Mal 2016). It has been used in massive DDoS attacks, including an attack on KrebsonSecurity in September 2016 which exceeded 600 Gbps (Krebs 2016), an attack on OVH in September 2016 which exceeded 1 Tbps (Klaba 2016), and an attack on Dyn in October 2016 (Hilton 2016) resulting in the cripple of some well-known websites such as GitHub, Twitter, Reddit, Netflix, Airbnb, and many others (Williams 2016). At its peak, Mirai infected 600k vulnerable IoT devices (Antonakakis et al. 2017), whose IP addresses were spotted in 164 countries (Herzberg et al. 2016). Since the source code for Mirai was published on hackforums.net (Anna-senpai 2016), the techniques can be digged deeply and may be adapted in other malware projects. The original creators of Mirai (i.e., Paras Jha, Josiah White, and Dalton Norman) has pleaded guilty in December 2017 (Department of Justice 2017) and sentenced to probation in September 2018 (Department of Justice 2018).

Foundations

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In this chapter, we first present our analysis of the released source code of the Mirai malware for its architecture, scanning, and prorogation strategy (Antonakakis et al. 2017; Kambourakis et al. 2017; Ling et al. 2018). We then discuss why Mirai did not get attention in its prorogation phase until it deployed the DDoS attack. Finally, we present a new variant of Mirai that can improve the propagation speed. The goal of the study is to understand the impact of Mirai as both a worm and botnet.

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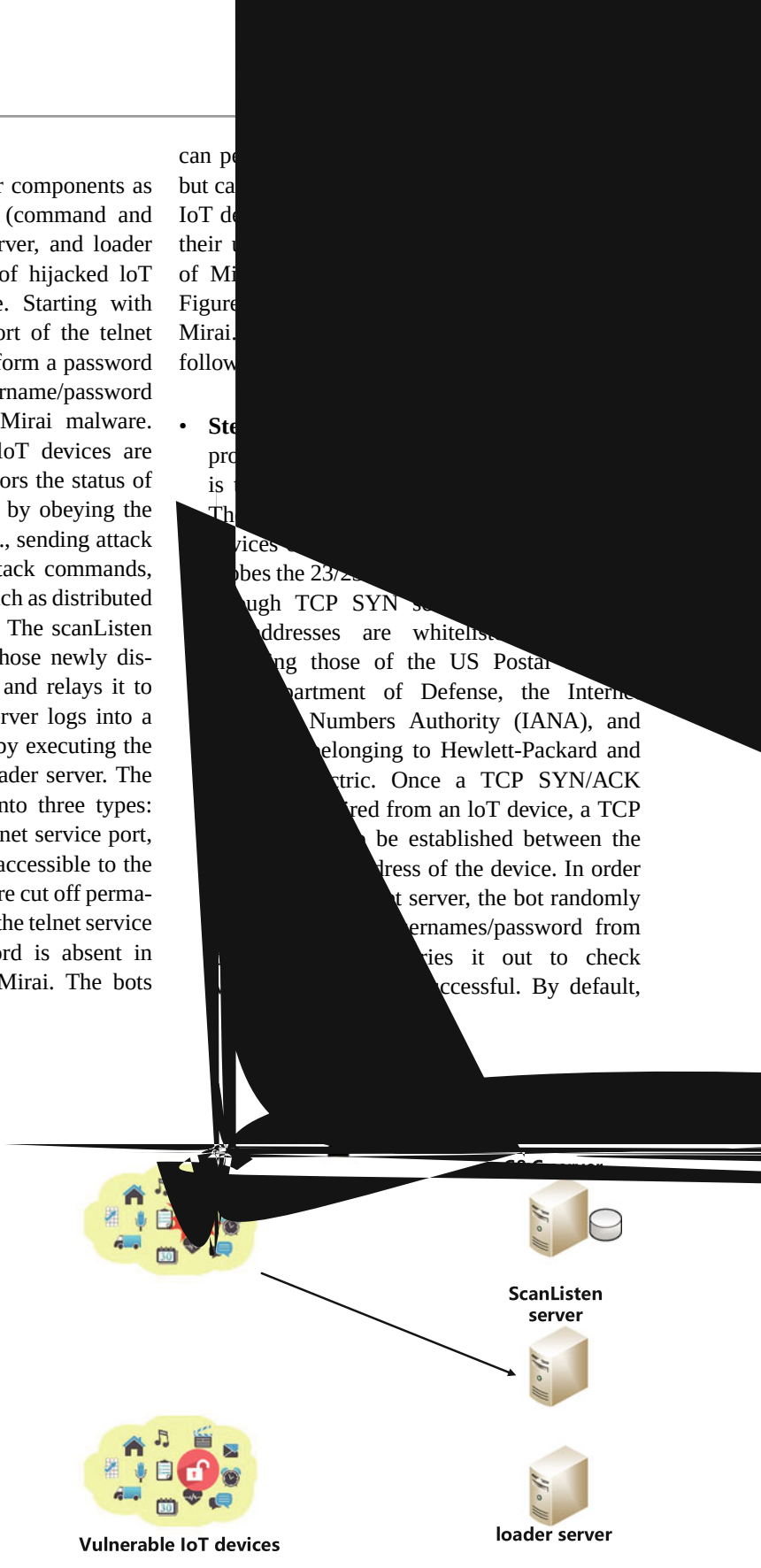
The Mirai botnet comprises four components as shown in Fig. 1: bots, a C&C (command and control) server, a scanListen server, and loader servers. The bots are a group of hijacked loT devices via the Mirai malware. Starting with a scanning procedure on the port of the telnet service, the bots continue to perform a password dictionary attack using the username/password list already hardcoded in the Mirai malware. In this way, some vulnerable loT devices are infected. The C&C server monitors the status of the botnet and controls the bots by obeying the commands from a botmaster, e.g., sending attack commands. On receiving the attack commands, the bots deploy various attacks such as distributed deny-of-service (DDoS) attacks. The scanListen server receives information of those newly discovered vulnerable IoT devices and relays it to the loader server. The loader server logs into a vulnerable device and infects it by executing the Mirai malware carried by the loader server. The IoT devices can be classified into three types: (1) IoT devices that close the telnet service port, i.e., 23/2323 port. They are not accessible to the bots since the TCP connections are cut off permanently; (2) IoT devices that open the telnet service port but their username/password is absent in the username/password list of Mirai. The bots



New Variants of Mirai and Analysis, Fig. 1
Propagation process of Mirai

the dictionary has altogether 62 pairs of usernames/password. However, the password cracking trials are no more than ten times for a target.

- **Step 2 – Bots reporting information to scanListen server**: After a bot compromises a vulnerable IoT device, it reports the information of the device to the scanListen server, including the IP address, the port, and the username/password of the target. The domain name and port of scanListen server are also hardcoded into the malware.
- **Step 3 – scanListen server relaying information to loader server**: The scanListen server receives the information of a compromised loT device from the bot and then forwards it to the loader server.
- **Step 4 – Loader server installing Mirai**: The loader server first builds a TCP connection with the compromised device and then logs onto the device with the cracked username/password. After its login, the loader server starts detecting file transmission tools like *wget* or *tftp* on the target system. If a transmission tool is available, the Mirai malware is directly downloaded from the loader server and executed. Otherwise, the loader server connects to the telnet port of the target, reads a tiny binary file whose function is similar to that of *wget*, and writes *echo* into the target device. The hex characters from the binary file constitute the string for *echo*. Then the output stream of *echo* is redirected into a file and saved at the target device. Therefore, the binary file is transmitted from the loader server to the target. By executing the file, the Mirai malware can be downloaded from the loader server. Once the Mirai is executed, it shuts down Telnet, SSH, and HTTP server on the compromised device to avoid the login of other malwares or administrators. Mirai also binds to port 48101 for the assurance that only one instance of the malwares is running on this device.
- **Step 5 – Bot registrating with C&C server**: Once the Mirai malware is installed and executed on a vulnerable device, the device builds a TCP connection, registers with the C&C server, and gets involved in the Mirai botnet. The domain name and port of the C&C server are hardcoded into the malware. Then the bot performs Step 1.
- **Step 6 – Botmaster commanding bots to conduct attacks**: A botmaster can command the bots to perform attacks by sending instructions via the C&C server. The Mirai malware can be activated to launch various attacks like UDP DoS attack, TCP DoS attack, HTTP attack, and GREP attack.
- **Step 7 – Botnet attacking a target**: Once the C&C server receives the attacking instructions from the botmaster, it conveys the commands to the bots. Finally, the bots perform attacks against a target.

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The scanning algorithm of the released source code of the Mirai is worth studying since it is the key to its propagation speed. Therefore, we thoroughly analyze the Mirai scanning algorithm in Algorithm 1. It is discovered that Mirai malware uses a uniform scanning strategy. Specifically, Mirai randomly scans public IP addresses and then randomly selects a pair of usernames/password from a hardcoded list for the dictionary attack. The TCP SYN scanning technique is employed to probe the 23/2323 port of a device for the purpose of determining whether the port is open. As can be seen from the Mirai source code, 160 IP addresses are randomly selected as target for the bot to scan. The bot sends TCP SYN packets to those IP addresses by using a raw socket. Then the raw socket is checked so as to obtain SYN+ACK packets.

As long as the bot receives a SYN+ACK packet, it establishes a TCP connection with the IP address in the non-blocking mode and records the connection in a table. After checking the raw socket and recording the connections, the bot checks the status of all TCP connections in the table. If a TCP connection fails to be built within 5 s, the bot will give up the connection request.

Conversely, if the TCP connection to the telnet port of an IP is established successfully, the bot will select a pair of usernames/password

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Algorithm 1: Mirai Scanning Algorithm

Require:
(a) μ - the number of SYN probes sent by Mirai each time,
(b) m - the size of a table,
(c) $table$ - TCP connection table,
(d) $table[i]$ - store the ith TCP socket in $table$,
(e) $table[i].state$ - TCP connection state of the ith entry of $table$, e.g., connecting or connected.
Ensure: Discover the vulnerable devices

```
1: while TRUE do
2:   if time interval since last SYN probe >= 1s then
3:     Send μ probes using a raw socket
4:   end if
5:   while TRUE do
6:     Read SYN+ACKs packets from the raw socket
7:     if error || no data for reading || no entries in
       table then
8:       break
9:     else if the ith entry of table is empty then
10:      Build a connection,
         table[i].state = connecting
11:    end if
12:  end while
13:  for i = 1 : m do
14:    if the connection in table[i] times out then
15:      if table[i].state == connected then
16:        re-connect(try times < 10), otherwise
           free table[i]
17:      else if table[i].state == connecting
         then
18:        free table[i]
19:      end if
20:    else if table[i].state == connecting
       then
21:      Set the table[i] in write file descriptor set
         (wr fdset)
22:    else if table[i].state == connected
       then
23:      Set the table[i] in read file descriptor set
         (rd fdset)
24:    end if
25:  end for
26:  Select the write and read file descriptors
27:  for i = 1 : m do
28:    if table[i] in wr fdset then
29:      if connection error for table[i] then
30:        free table[i]
31:      else if connection success for table[i]
         then
32:        table[i].state = connected
33:      end if
34:    end if
35:    if table[i] in rd fdset then
36:      while TRUE do
37:        if connection error for table[i] then
38:          re-connect(try times < 10), otherwise
             free table[i]
39:          break
40:        else if no data for reading then
41:          break
42:        else if data for the last command then
43:          if login success then
44:            report to scanListen server
45:          else if login fail then
46:            re-connect(try times < 10),
               otherwise free table[i]
47:          end if
48:        else
49:          send one command
50:        end if
51:      end while
52:    end if
53:  end for
54: end while
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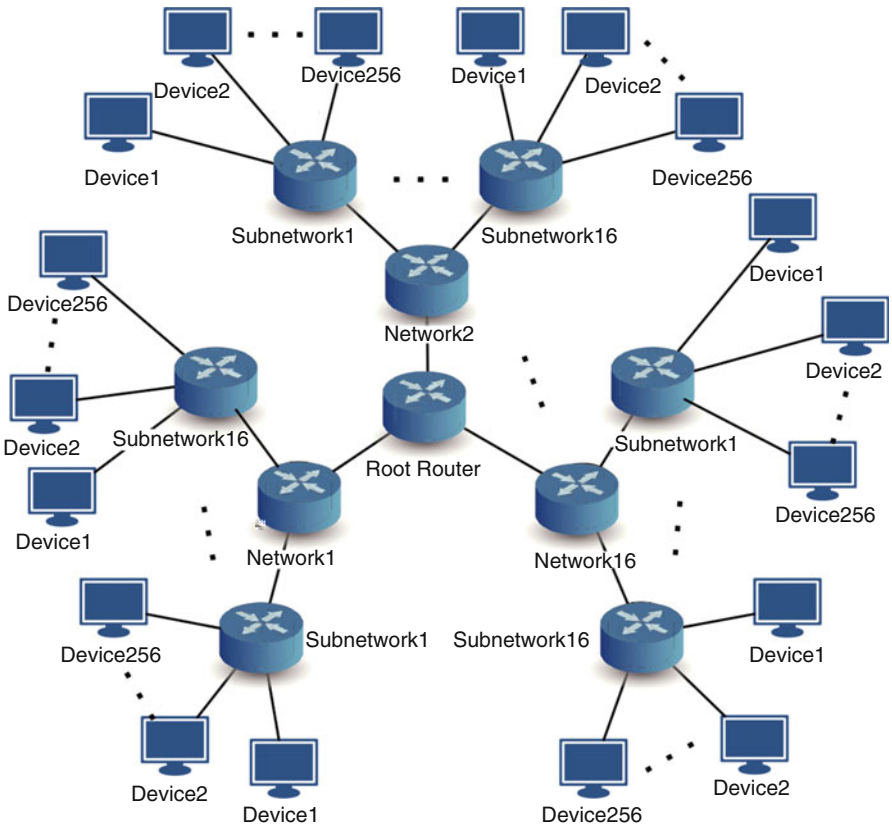
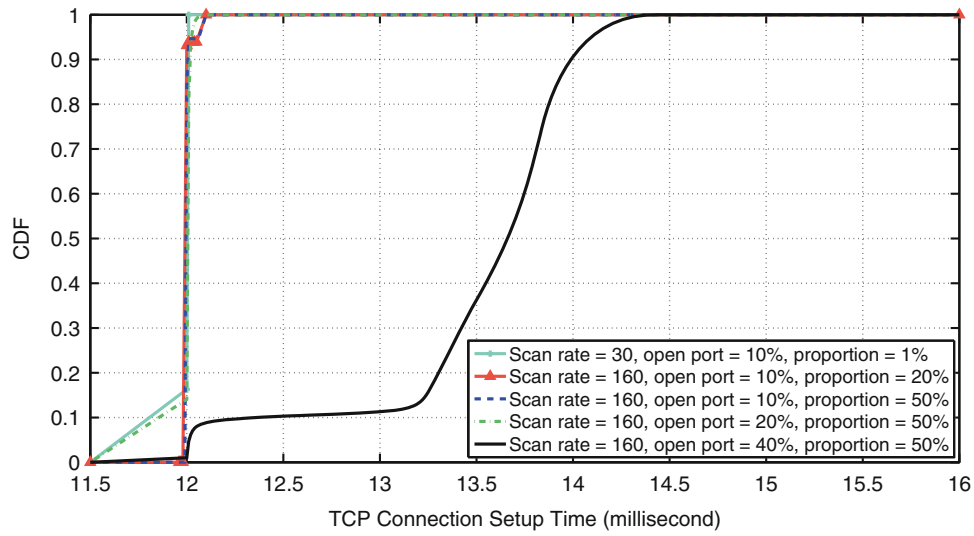
at random from the hardcoded list. Meanwhile, according to the feedback from the target device, the login can be verified as either a success

We simulate the original Mirai propagation using NS3. Recall that we divide the IP address space into three categories. We use empirical data to set the number of the devices in each category. Mirai grows to a peak of 600,000 infections at the end of November 2016 (Antonakakis et al. 2017), and the total number of IP addresses is 3,417,112,576 besides the IP addressed in the Mirai whitelists. Therefore, the proportion of vulnerable IoT devices is 0.0176%. Additionally, according to the results shown in ZoomEye (Zoo 2017), 11.1% online hosts open the telnet ports. To simplify the calculation, we round the proportions of the devices with open telnet ports and vulnerable telnet services to the nearest integer. Thus, in our simulation, we assume 10% of IoT devices in the IP space open the telnet port and 1% of the devices with the telnet service are vulnerable. Assume that the total number of devices in our simulated network is 65536. By using Monte Carlo method, we select 6325 devices that open telnet port, and 64 devices can be compromised by Mirai malware. Due to the limitation of computing power of IoT devices, the empirical results from Figure 6 in Antonakakis et al. (2017) show that the scanning bandwidth of 80% bots is smaller than 2000 Bps. Since the size of a TCP SYN scanning packet is 74 bytes, most bots can only probe around 30 IP addresses to scan their telnet ports in each round, rather than 160 IP addresses used in the Mirai source code. Thus, we change the scanning rate to 30 in our simulation. Figure 2 illustrates the network topology used in the simulation experiment. We use the NS3 global routing by building a global routing database for the topology using a Dijkstra Shortest Path First (SPF) algorithm, and we set the throughput of devices and routers as 1000 Mbps. The TCP connection setup time between a bot and a telnet port opened device



New Variants of Mirai and Analysis, Fig. 2 Network topology used in the simulation experiment



New Variants of Mirai and Analysis, Fig. 3 TCP connection setup time distribution with different configurations

New Variants of Mirai and Analysis, Table 1 The proportions of devices with open telnet port and vulnerable telnet service

Devices with open telnet port	Devices with telnet service are vulnerable
10%	20%
10%	50%
20%	50%
40%	50%

is used to determine if the network is congested. Figure 3 illustrates that the Mirai does not cause network congestion by using empirical parameters in the simulation. Therefore, we can infer that the infected devices cannot generate a large amount of propagation traffic due to the limited computing power of vulnerable IoT devices.

Besides the limitation of IoT device computing power, another reason why Mirai does not cause network congestion is that the proportions of devices with open telnet port and vulnerable telnet service, respectively, are small. We assume the bot can probe 160 IP addresses in each round as the source code set and set two proportions in Table 1. The NS3 simulation results in Fig. 3 show that until we set 40% of IoT devices in the IP space with open telnet port and 50% of the devices with telnet service that are vulnerable, the time of TCP connection setup becomes longer. At that point, the Mirai propagation has caused network congestion. Therefore, Mirai cannot cause network congestion by scanning and infecting a small number of devices with open telnet port and vulnerable telnet service.

According to the real-world observation (Antonakakis et al. 2017), the proportion of devices with open telnet port and vulnerable telnet service are much lower than the 40% and 50%, respectively, and the limitation of IoT devices computing power cannot probe 160 IP addresses every round either. Therefore, Mirai did not cause network congestion and get attention during the propagation.

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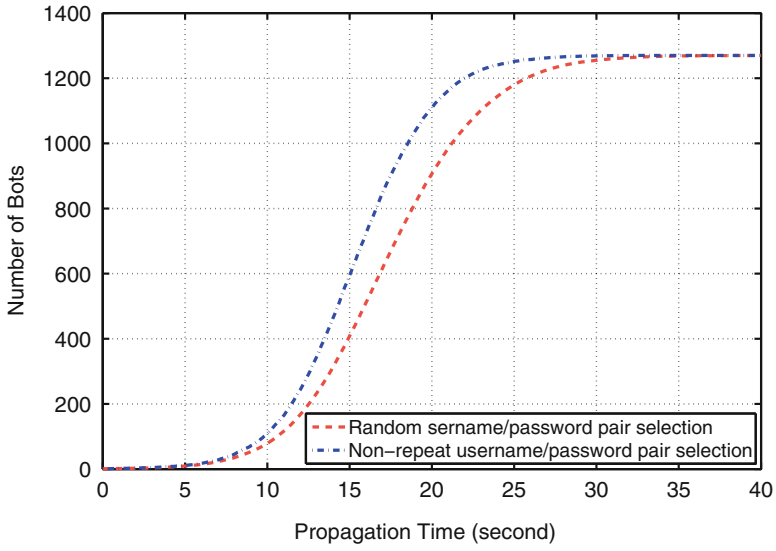
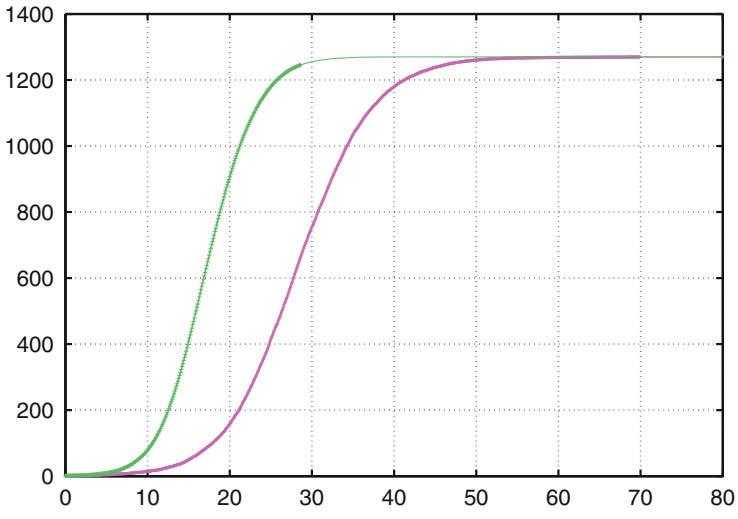
We design new scanning strategies in order to boost the propagation. In contrast to the malware such as the Code Red worm (Zou et al. 2002) that exploits software vulnerabilities, the Mirai malware not only scan the devices to discover the open telnet port but also crack the username/password using a hardcoded dictionary so as to successfully infect IoT devices. Therefore, the propagation speed of Mirai is much slower than that of the Code Red worm.



New Variants of Mirai and Analysis, Fig. 4 The Mirai propagation speed using different cracking strategies



New Variants of Mirai and Analysis, Fig. 5 The Mirai propagation speed using different password cracking times

propagation speed ensues. Another observation is that as the number of attempts increases, the gain (acceleration) of the propagation speed falls. Thus we can devise a new variant of Mirai by keeping the username/password cracking times at 20 so as to fasten the Mirai propagation speed.

Future Directions

In this chapter, we study Mirai and propose new Mirai variants. We carefully introduce the propagation process of Mirai. Extensive NS3 simulations suggest that if the number of vulnerable devices is small, infected devices would not cause network congestion. This is why Mirai did not get attention during its propagation. To understand the potential impact of future Mirai attacks, we study new scanning strategies of Mirai that may