Pwn2Own'ing the TP-Link Archer A7

THCon 2022

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$ whoami

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Summary

- We will guide you through our journey at Pwn2Own
  - Presentation of the competition and how it works
  - Vulnerability research process
  - Discovery of CVE-2021-27246
  - Exploitation
  - Q&A

- Stay with us, it won’t be an hardcore technical talk

Pwn2Own in 2 minutes

- Competition organized by the Trend Micro Zero Day Initiative, during CanSecWest
- A list of products is announced, along with rules
  - OS, browsers, consumer electronics (phones, watches, routers)
  - Products are be up-to-date (24 hours before) in their default configuration
  - You have to prove remote code execution, without authentication
- Trend Micro isn't a broker!
  - Acquisitions are disclosed to vendors with the goal of getting them fixed
- You get a cool challenge and maybe a few $$

Pwn2Own in 2 minutes

- We took part of Pwn2Own Tokyo 2020
  - Contest on November 2, 2020: 3 months to prepare
- Remote participation is now possible
  - You need to provide the exploit(s) and a explanation of each bug
  - ZDI will run it for you, everything is live streamed
  - Drawback: you are not allowed to fix the exploit(s) between attempts
- Teams order is random, duplicates are not rewarded
- Several bugs killed at the last minute

TP-Link AC1750

- Mid-end Wi-Fi router
- Models A7 and C7 are very similar
  - The later has Alexa support (??)
  - 720 Mhz MIPS CPU, 8MB of flash, 128MB of RAM
  - 802.11ac, 4 LAN slots + 1 WAN
- < 100€, quite popular in the custom firmware scene
- Second year in a row at Pwn2Own
  - Bugs are found and disclosed every year
  - No major change between versions
- LAN-side vs WAN-side

Initial access - UART

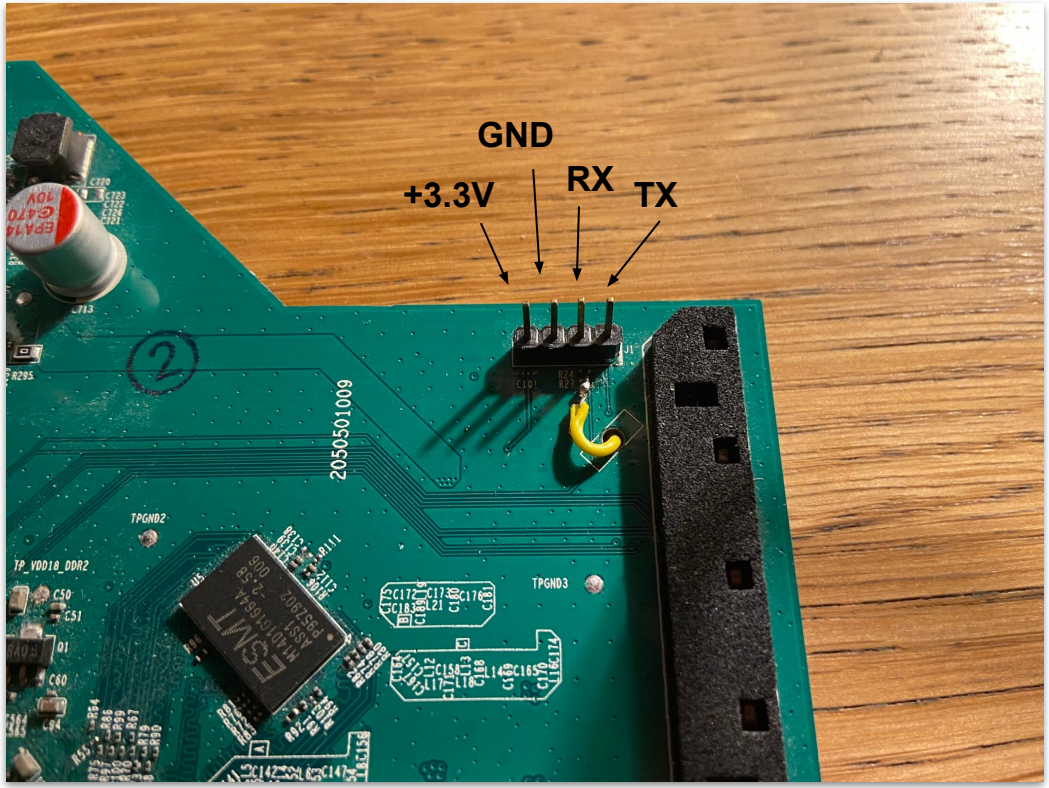
- “Free” shell access on consumer electronics is rare
- First step of any research on embedded systems
  - UART / JTAG are still easy to locate
    - Physical presence, datasheets
    - Not always restricted
  - Debugging capabilities are incredibly useful
- Use public resources
  - (GitHub Code Search is a game changer nowadays)

Initial access - UART

- We won’t cover the UART discovery
  - “Hacker's Guide to UART Root Shells” by Team Flashback
    - https://www.youtube.com/watch?v=01mw0oTHwxg

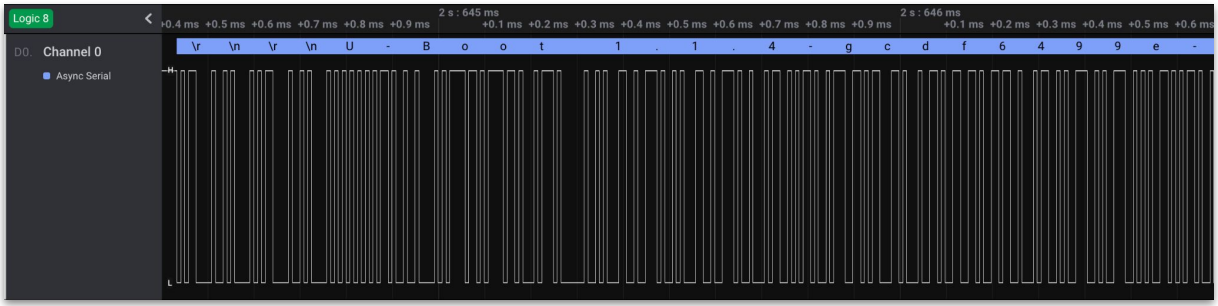
- No downgrade protection
  - You can also use exploits from previous years
  - Requires persistence (not investigated in our case)

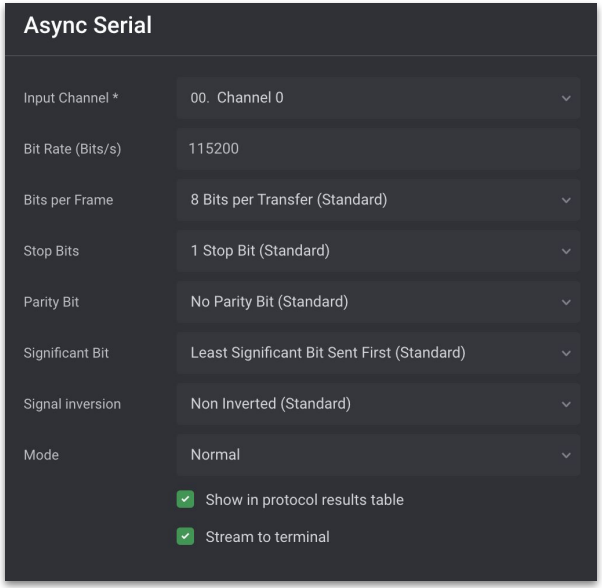
Initial access - UART



Initial access - UART

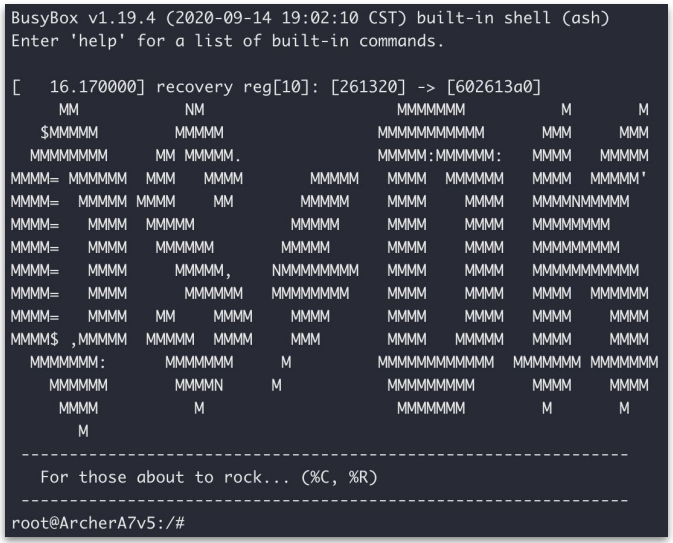
- A good logic analyzer will help finding the right parameters to decode the serial communication
  - e.g. Saleae + Logic 2 + 5 minutes





Initial access - UART

- Plug everything, reboot the device
  - `minicom -8 -b 115200 -D /dev/tty.usbmodem*`
- Access to the bootloader prompt
  - `U-Boot 1.1.4`
  - Useful if we need to reflash the device
- Shell access as `root`
- Limited OpenWrt environnement
  - `MIPS OpenWrt Linux-3.3.8`



Initial access - Environment

- Compilation of useful tools (`gdbserver`, `strace`, `busybox` with all applets)
  - Target is a MIPS32 big endian CPU, supported by Buildroot
    - `BR2_MIPS_SOFT_FLOAT=y`
    - `BR2_TOOLCHAIN_BUILDROOT_LIBC="musl"`
- Customized Dropbear is running, authentication is disabled
  - Kill it and remove a few options over UART: remove `-C`, add `-L`
  - Use it to copy additional binaries
- Don’t try anything fancy
- Time to hunt for vulnerabilities!

Attack surface

- Previous work by other contestants
  - https://www.thezdi.com/blog/2020/4/6/exploiting-the-tp-link-archer-c7-at-pwn2own-tokyo
  - https://labs.f-secure.com/advisories/tp-link-ac1750-pwn2own-2019/
- Recent firmwares are available on tp-link.com
- DHCP on the WAN
- Only a few services listen on the LAN
  - `dropbear`, `udpxy`, `uhttpd`, `tdpServer`
- `/usr/bin/tdpServer`
  - UDP, port 20002, LAN-side
  - Simple protocol (binary header, JSON payload)
  - Already documented, patented
  - Runs as `root`

```
struct tdp_packet {
    uint8_t version;
    uint8_t type;
    uint16_t opcode;
    uint16_t len;
    uint8_t flags;
    uint8_t _padding;
    uint32_t device_serial;
    uint32_t checksum;
    uint8_t data[1024];
};
```

Attack surface

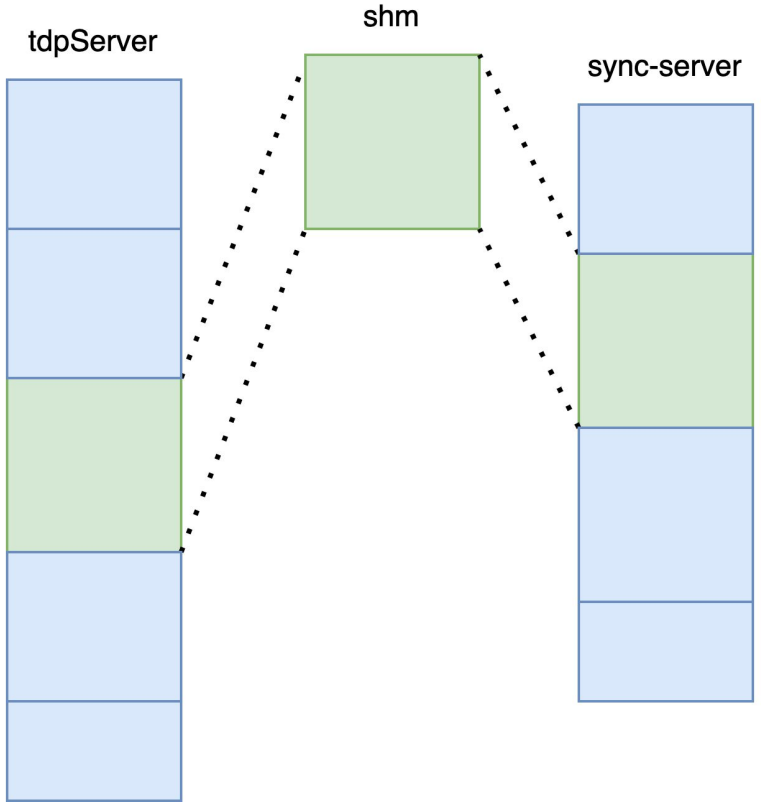
- Ghidra = <3
- `tdpServer` decrypts `data` with a fixed key and parses it as JSON (kind of)

```
key = b'TPONEMESH_Kf!xn?gj6pMAt-wBNV_TDP'[0:16]
```

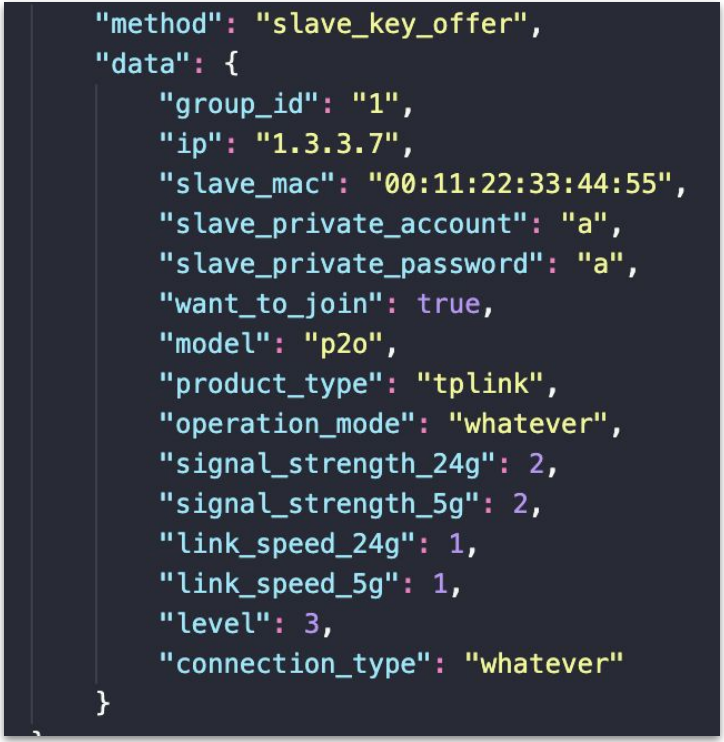
- Most handlers are related to OneMesh
  - It seems related to proprietary configuration synchronization for roaming
  - Devices advertise themselves
  - Crafted a bunch of `scapy` scripts
  - After a first review, a few DoS but nothing exploitable
  - *Plot twist: last year's vulnerability was not really fixed, but we missed it*

Attack surface

- Each advertised device is added in a shared memory area (up to 64)
  - Stores pairs of MAC / IP of clients as strings
  - Who's reading from it? New attack surface: `sync-server`



Research and discovery of CVE-2021-27246



```
"method": "slave_key_offer",
"data": {
    "group_id": "1",
    "ip": "1.3.3.7",
    "slave_mac": "00:11:22:33:44:55",
    "slave_private_account": "a",
    "slave_private_password": "a",
    "want_to_join": true,
    "model": "p2o",
    "product_type": "tplink",
    "operation_mode": "whatever",
    "signal_strength_24g": 2,
    "signal_strength_5g": 2,
    "link_speed_24g": 1,
    "link_speed_5g": 1,
    "level": 3,
    "connection_type": "whatever"
}
```

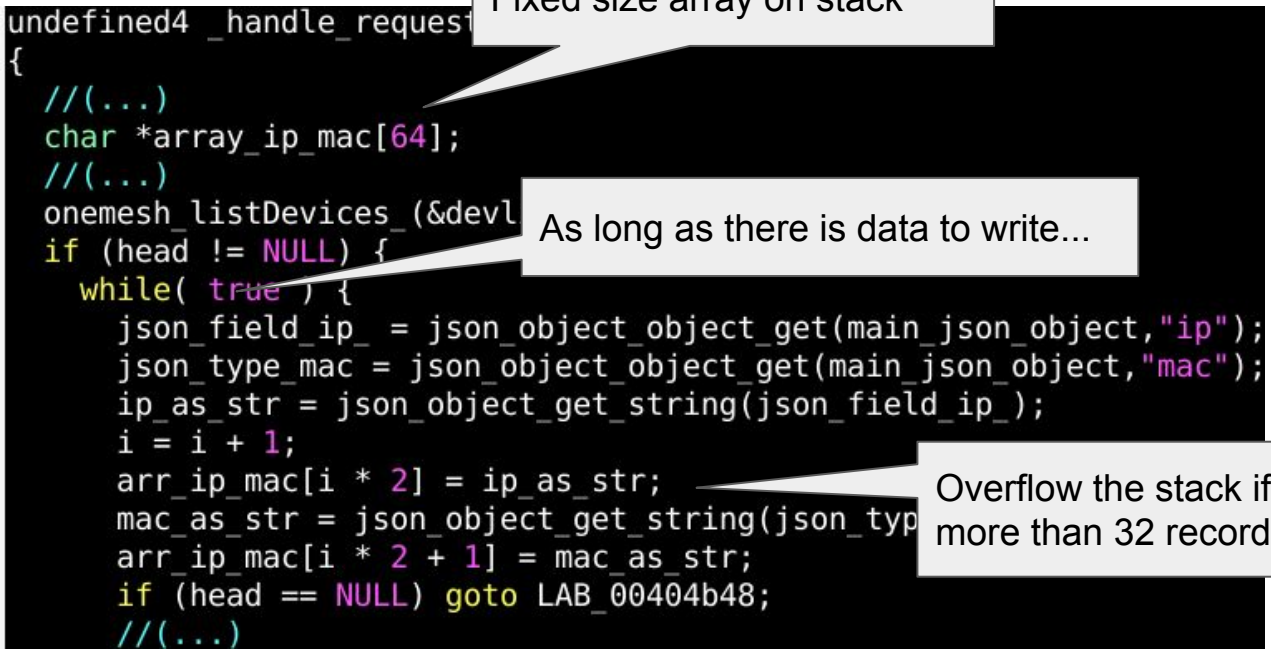
Research and discovery of CVE-2021-27246

- `sync-server`: a vulnerable function is found!

```
undefined4 _handle_request_clients_async(void)
{
  //(...)
  char *array_ip_mac[64];
  //(...)
  onemesh_listDevices_(&devlist);
  if (head != NULL) {
    while( true ) {
      json_field_ip_ = json_object_object_get(main_json_object,"ip");
      json_type_mac = json_object_object_get(main_json_object,"mac");
      ip_as_str = json_object_get_string(json_field_ip_);
      i = i + 1;
      arr_ip_mac[i * 2] = ip_as_str;
      mac_as_str = json_object_get_string(json_type_mac);
      arr_ip_mac[i * 2 + 1] = mac_as_str;
      if (head == NULL) goto LAB_00404b48;
      //(...)
```

Research and discovery of CVE-2021-27246

- `sync-server`: a vulner[illegible]und!



Research and discovery of CVE-2021-27246

- Test scenario
  - Send 32+ messages to `tdpServer` with different IP / MAC
  - Wait for `sync-server` to read them: crash!
- A PoC is written and confirms the bug
  - “Illegal instruction” and not “Segmentation Fault”?

```
sync-server:_handle_request_clients_async:2494: [DBG] count is 49
sync-server:_handle_request_clients_async:2503: [DBG] Infile: /tmp/sync-server/
‹ → request-input-2046063169-25104
sync-server:_handle_request_clients_async:2508: [DBG] Outfile: /tmp/sync-server/
‹ → request-output-1502619911-25104
Illegal instruction
root@ArcherC7v5:~#
```

Exploitation

- This bug seems OK
  - Not in a network daemon, less likely to be found by another team
- Some good points
  - No stack canary
  - Non-PIE binary
  - IP and MAC formats are not validated, only limited in size

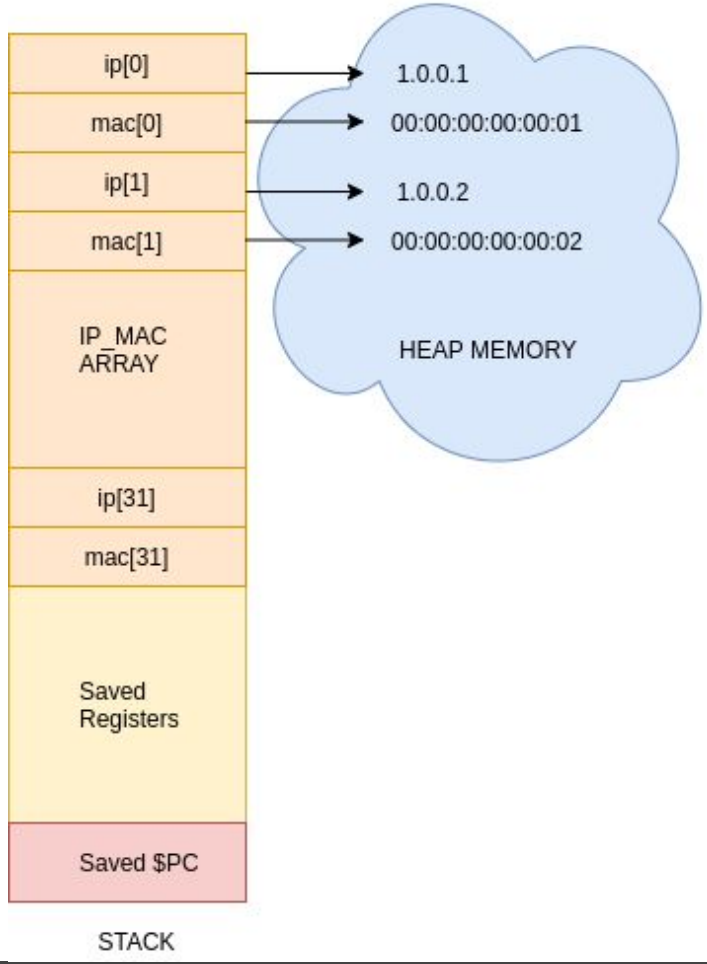
Exploitation

- And bad points
  - Full ASLR
  - Integrity checks on JSON data
  - No direct interaction with `sync-server`
  - Everything is sensitive: we must avoid crashing `tdpServer`
  - MAC addresses can’t be longer than 17 bytes = 4 MIPS32 instructions

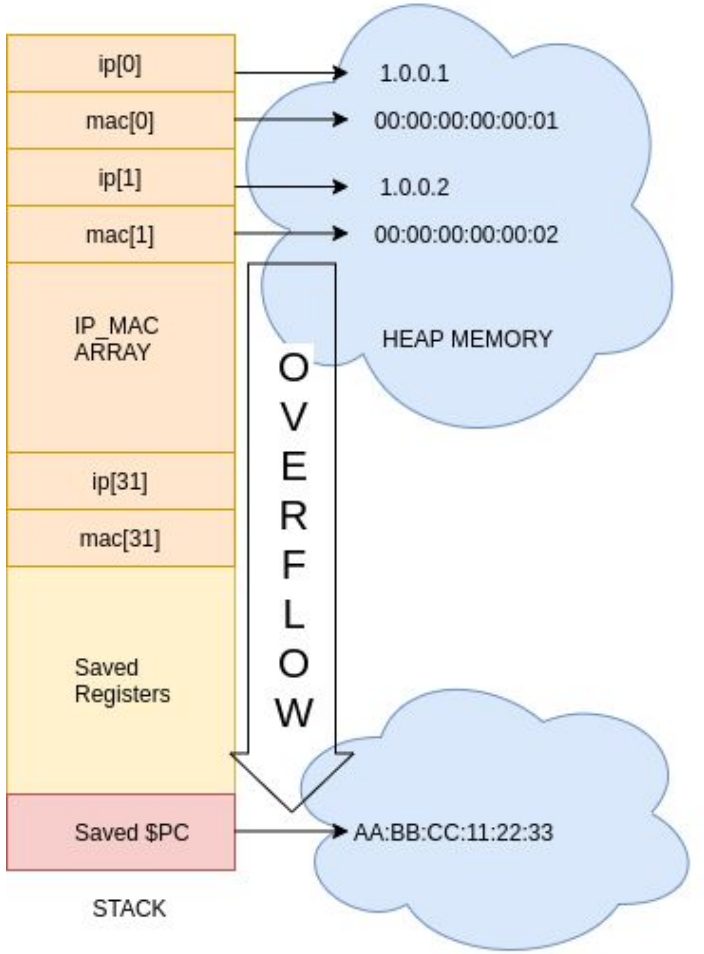
Exploitation - ASLR

- ASLR is trivially bypassed!
- The stack overflow writes a pointer to data we control in the heap
  - `array_ip_mac[i]=ip_as_str;`
  - `array_ip_mac[i+1]=mac_as_str;`
- `$pc` is restored and points to a MAC address we control
- Heap is RWX!

Exploitation - ASLR



Exploitation - ASLR



Exploitation - JSON encoding

- We inject a MAC address
  - only 17 bytes long, not that much…
  - string only
  - with the help of unicode we can use any chars (except nul)
- Shellcode without with NULLs is an acceptable constraint
- Instruction in mips are 4-bytes
  - Maximum 4 instruction

Exploitation - shellcoding with 4 instructions

- Idea: why not `system(cmd)`?
- `sync-server` is not compiled as PIE
  - `0C 10 07 14 jal system`
  - No NULL byte
- `$s0`, `$s2`, `$s4` and `$s6` contains pointers to IPs we advertised
  - `02 40 20 25 move $a0,$s2`
  - No NULL byte
- Only two instructions needed
- We have to decide which command to execute
  - No `telnetd`, no `netcat`, a stripped down `busybox` with few applets…

Exploitation - Final Step

- TP-Link ships a debug daemon called `tddp` riddled with trivial vulnerabilities
  - Not started by default
- `system("tddp")`
- Inject a second stage through `tddp`
  - Start a reverse shell
- Exploit is reliable
  - Exploit takes time because `sync-server` is asynchronous and terribly slow

Final Steps

- Whitepaper and exploit sent to ZDI the week before the event
- … but a new update is released a few days before the event
  - Most contestants cancel their participation
  - Our bug is still working (??)
  - *Plot twist of the plot twist: last year's bug has been patched*
- Organisers schedule a Zoom call before the attempt
  - Explain the setup, show the hardware and the version
  - Different firmware but `sync-server` is the same binary
- Exploit is launched on live stream, without showing the script output
- 3 attempts, individual limit of 5 minutes
  - 2 x 80 seconds feels like an eternity

Win!

Publication

- To publish details, either
  - Wait for 3 months
  - Vulnerability is patched by editor
- No further hardening
  - Same compilation flags
  - The binary `tddp` is still present

```
while ( 1 )
{
  v8 = *(_DWORD *)(v6 + 4);
  v6 = *(_DWORD *)(v6 + 8);
  if ( json_object_get_type(v8) != 4 )
    break;
  if ( !json_object_object_get(v8, "ip") )
    break;
  ip = json_object_object_get(v8, "ip");
  mac = json_object_object_get(v8, "mac");
  v11 = mac;
  if ( !ip || !mac || v7 >= 64 )
    break;
```

Conclusion

- The 90’s are calling
  - Most ~ modern exploit mitigations are missing
  - Patches are both rushed... and delayed to the last minute
- Pwn2Own is fun
  - New categories are more accessible than ever (printers, routers)
  - Organizers will do everything to help you before / during the event
  - The TP-Link AC1750 is still here ;-)
- Everything is available on GitHub
  - synacktiv/CVE-2021-27246_Pwn2Own2020
- Hack'n Speak episode with Amat Cama

Q&A

Thank you for your attention!

We'll be happy to take questions :-)