Pwn2Own’ing the TP-Link Archer A7

BARBHACK 2021

@0xMitsurugi - @swapgs

$ whoami

- @0xMitsurugi
  - Security Ninja at Synacktiv (Paris / Lyon / Rennes / Toulouse / Remote)
- @swapgs
  - Vulnerability Researcher at SonarSource (Geneva / Annecy / Bochum / Austin / Remote)
  - Work done during prior employment at Synacktiv, no affiliation between both companies

Summary

- We will guide you through our journey at Pwn2Own
    - Presentation of the competition and how it works
    - Initial setup
    - Discovery of CVE-2021-27246
    - Exploitation
    - Q&A
- Stay with us, it won’t be a crazy hardcore insane technical talk

Pwn2Own in 2 minutes

- Bi-annual competition by the Trend Micro ative, taking place during CanSecWest

- A list of products is announced, along with rules
    - OS, browsers, consumer electronics (phones, watches, routers)
    - Products will be to be up-to-date (24 hours before) in 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
  - Original announcement: July 28, 2020
  - Contest deadline: November 2, 2020
- Remote participation is now possible
  - ZDI will run it for you, everything is live streamed
  - Drawback: you are not allowed to fix the exploit(s) between attempts
  - You need to provide the exploit(s) and a full explanation of each bug beforehands
- Teams order is random, duplicates are not rewarded
  - “Partial win”
- Several bugs ready but only participated in the *Routers* category

TP-Link AC1750

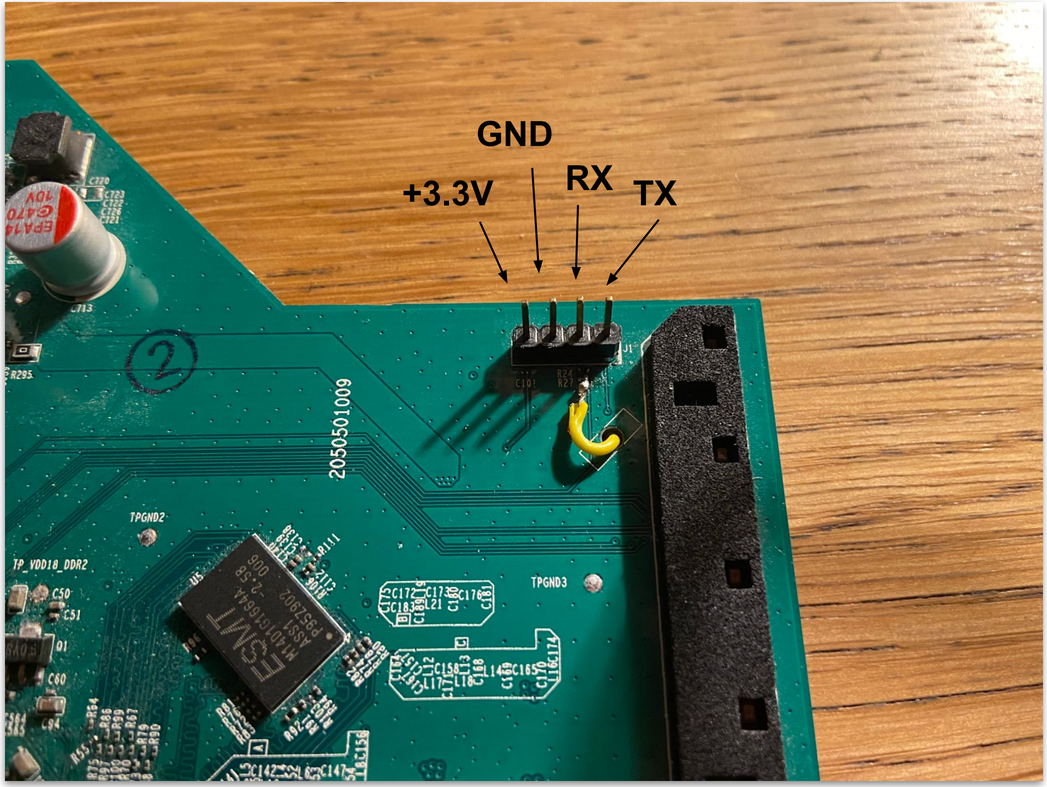
- Mid-end Wi-Fi router
- Models A7 and C7 are very similar
    - The later has Alexa support (??), mostly sold on Amazon (15k+ evaluations)
    - 720 Mhz MIPS CPU, 8MB of flash, 128MB of RAM
    - 802.11ac, 4 LAN slots + 1 WAN
- < 100€, quite popular in the custom firmware scene
    - Some documentation related to the OpenWrt support is public
- Second year in a row at Pwn2Own
    - Bugs are found and disclosed every year
    - No major change between versions

tp-link
AC1750 Wireless
Dual Band
Gigabit Router
Archer C7
High-Speed Wi-Fi for Faster Connections Across Your Home
450Mbps + 1300Mbps Dual Band Wi-Fi
Gigabit Ports
USB 2.0 Port

Initial access - UART

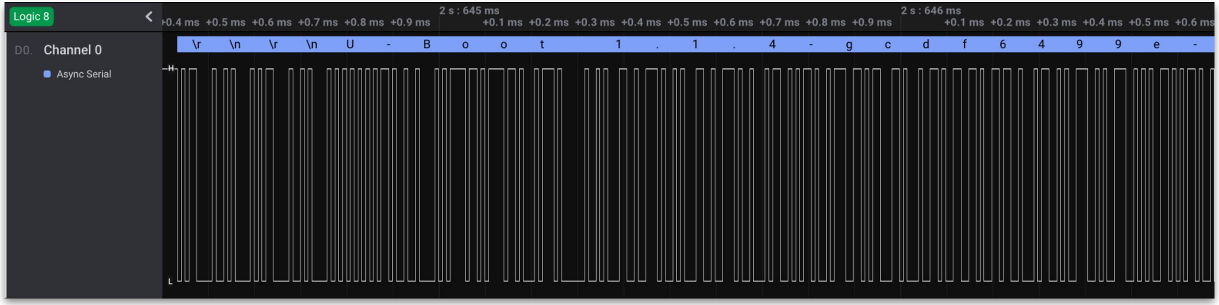
- “Free” shell access on consumer electronics is rare
- First step of any research on embedded systems
  - UART / JTAG are often easy to locate
    - Physical presence, datasheets
    - Not always restricted
  - Debugging capabilities are incredibly useful
- We won’t cover the UART discovery
  - Check out Team Flashback’s great video https://www.youtube.com/watch?v=01mw0oTHwxg
- No downgrade protection, you can also use exploits from previous years
  - Requires persistence (not investigated)

Initial access - UART

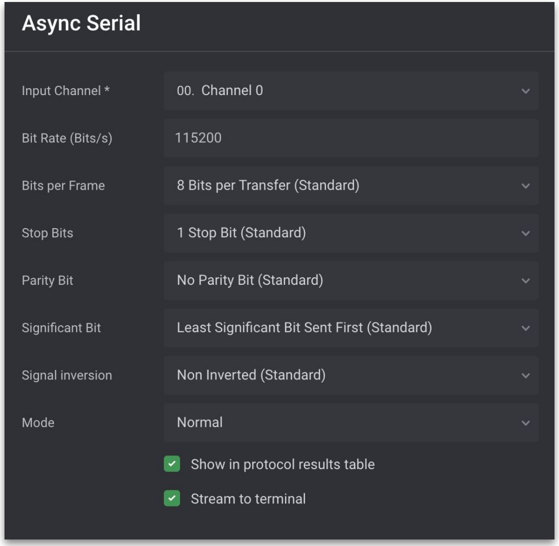


Initial access - UART

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


Logic 8
D0. Channel 0
Async Serial
+0.4 ms +0.5 ms +0.6 ms +0.7 ms +0.8 ms +0.9 ms
2 s : 645 ms
+0.1 ms +0.2 ms +0.3 ms +0.4 ms +0.5 ms +0.6 ms +0.7 ms +0.8 ms +0.9 ms
2 s : 646 ms
+0.1 ms +0.2 ms +0.3 ms +0.4 ms +0.5 ms +0.6 ms
H
L

```
\r \n \r \n U - B o o t   1 . 1 . 4 - g c d f 6 4 9 9 e -
```



Async Serial

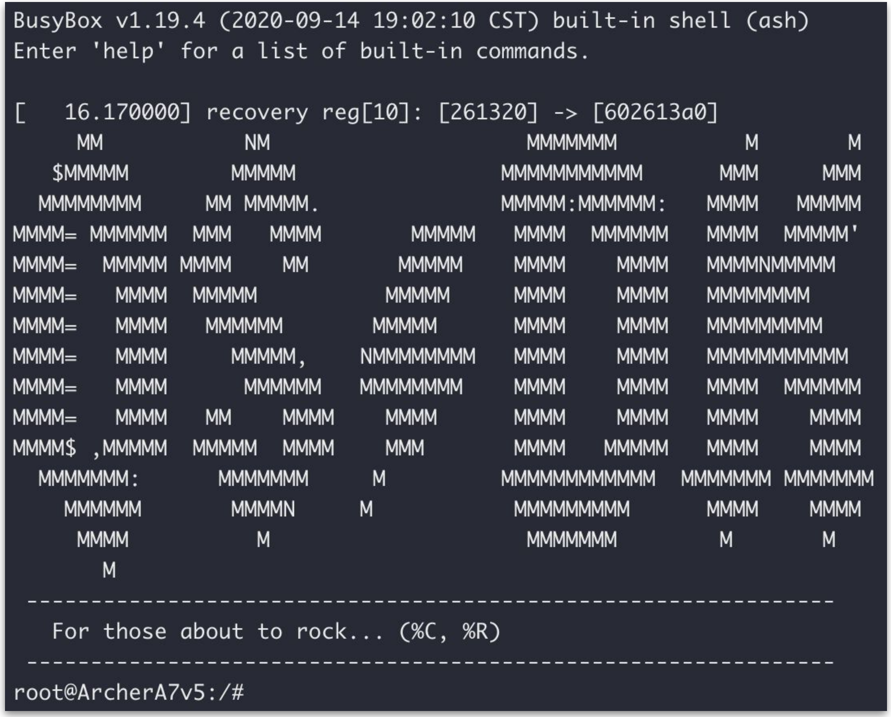
Input Channel *	00. Channel 0
Bit Rate (Bits/s)	115200
Bits per Frame	8 Bits per Transfer (Standard)
Stop Bits	1 Stop Bit (Standard)
Parity Bit	No Parity Bit (Standard)
Significant Bit	Least Significant Bit Sent First (Standard)
Signal inversion	Non Inverted (Standard)
Mode	Normal

☑ Show in protocol results table

☑ Stream to terminal

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`



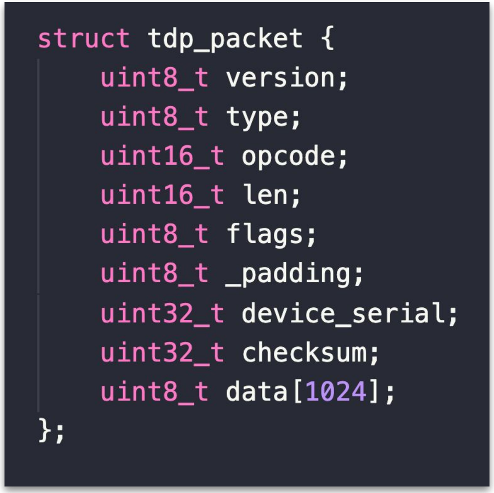
```
BusyBox v1.19.4 (2020-09-14 19:02:10 CST) built-in shell (ash)
Enter 'help' for a list of built-in commands.

[   16.170000] recovery reg[10]: [261320] -> [602613a0]
     MM           NM                    MMMMMMM          M       M
   $MMMMM        MMMMM                MMMMMMMMMMM      MMM     MMM
  MMMMMMMM     MM MMMMM.              MMMMM:MMMMMM:   MMMM   MMMMM
MMMM= MMMMMM  MMM   MMMM       MMMMM   MMMM  MMMMMM   MMMM  MMMMM'
MMMM=  MMMMM MMMM    MM       MMMMM    MMMM    MMMM   MMMMNMMMMM
MMMM=   MMMM  MMMMM          MMMMM     MMMM    MMMM   MMMMMMMM
MMMM=   MMMM   MMMMMM       MMMMM      MMMM    MMMM   MMMMMMMMM
MMMM=   MMMM     MMMMM,    NMMMMMMMM   MMMM    MMMM   MMMMMMMMMMM
MMMM=   MMMM      MMMMMM   MMMMMMMM    MMMM    MMMM   MMMM  MMMMMM
MMMM=   MMMM   MM    MMMM    MMMM      MMMM    MMMM   MMMM    MMMM
MMMM$ ,MMMMM  MMMMM  MMMM    MMM       MMMM   MMMMM   MMMM    MMMM
  MMMMMMM:      MMMMMMM     M         MMMMMMMMMMMM  MMMMMMM MMMMMMM
    MMMMMM       MMMMN     M           MMMMMMMMM      MMMM    MMMM
     MMMM          M                    MMMMMMM        M       M
       M
 ---------------------------------------------------------------
   For those about to rock... (%C, %R)
 ---------------------------------------------------------------
root@ArcherA7v5:/#
```

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 already running, but authentication is disabled
  - Kill it and remove a few options over UART: remove `-C`, add `-L`
  - Use it to copy additional binaries
- Don’t enjoy it too much though
- Time to hunt for vulnerabilities!

Attack surface

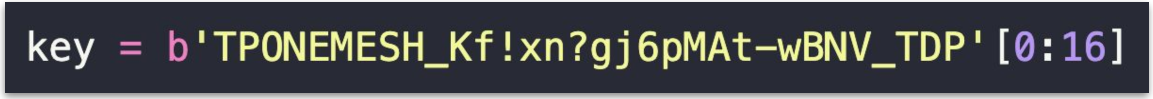
- Previous work by other contestants
  - https://www.thezdi.com/blog/2020/4/6/exploiting-the-tp-link-archer-c7-at-pwn2own-tokyo
  - https://labs.f-secure.com/advisories/tp-link-ac1750-pwn2own-2019/
- Recent firmwares are available on tp-link.com
- DHCP on the WAN
- Only a few services listen on the LAN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



```c
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

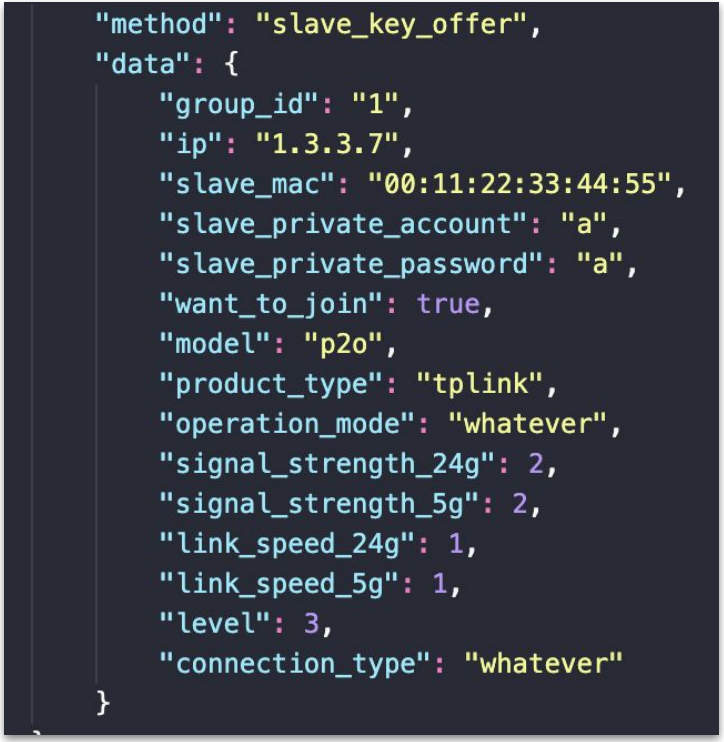
- Ghidra = <3
- `tdpServer` decrypts `data` with a fixed key and parses it as JSON (kind of)



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

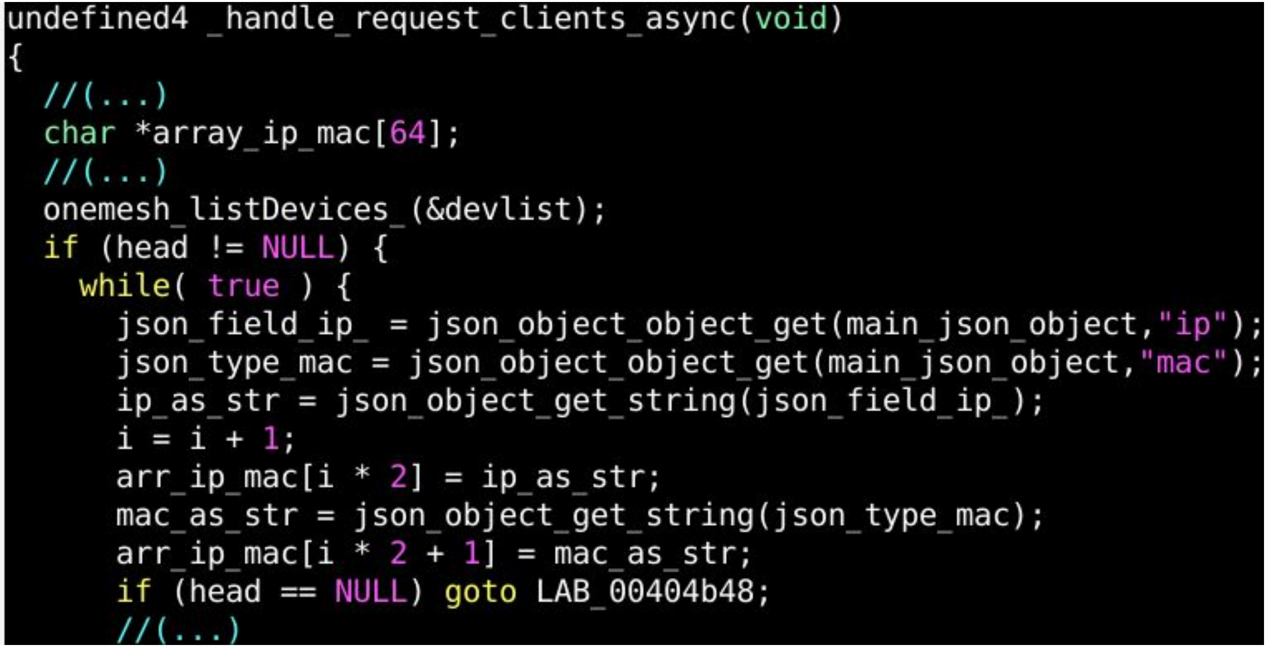
Research and discovery of CVE-2021-27246



```
    "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

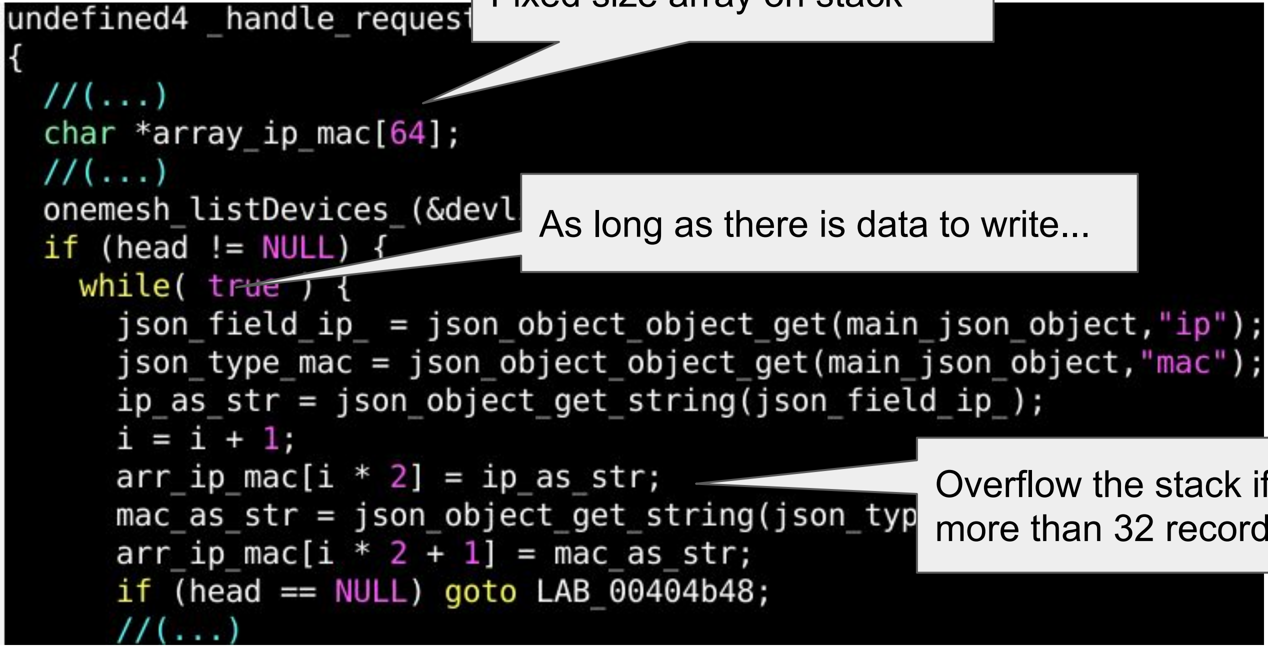
- `sync-server`: a vulnerable function is found!



```
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 vulnerable fun



```
undefined4 _handle_request
{
  //(...)
  char *array_ip_mac[64];
  //(...)
  onemesh_listDevices_(&devl
  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_typ
      arr_ip_mac[i * 2 + 1] = mac_as_str;
      if (head == NULL) goto LAB_00404b48;
      //(...)
```

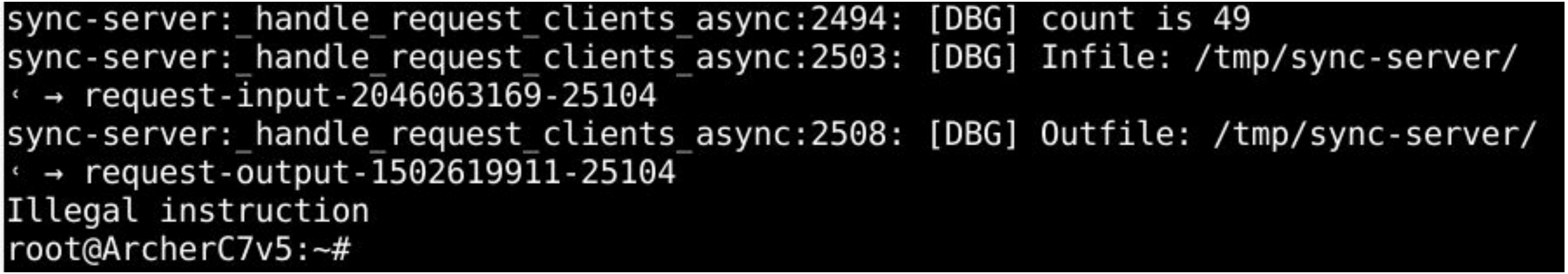
Fixed size array on stack

As long as there is data to write...

Overflow the stack if more than 32 records...

Research and discovery of CVE-2021-27246

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



```
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:~#
```

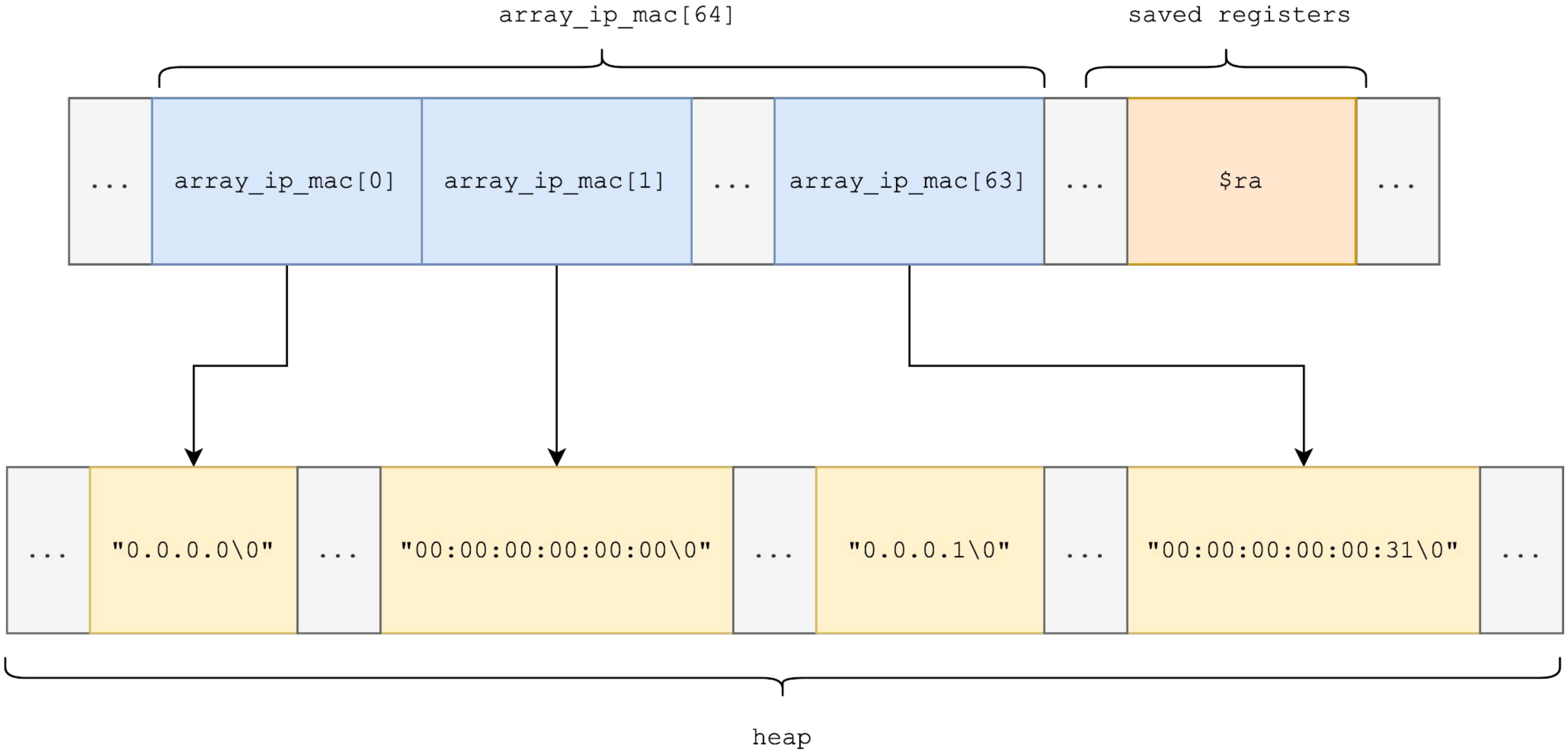
Exploitation

- 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
- 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

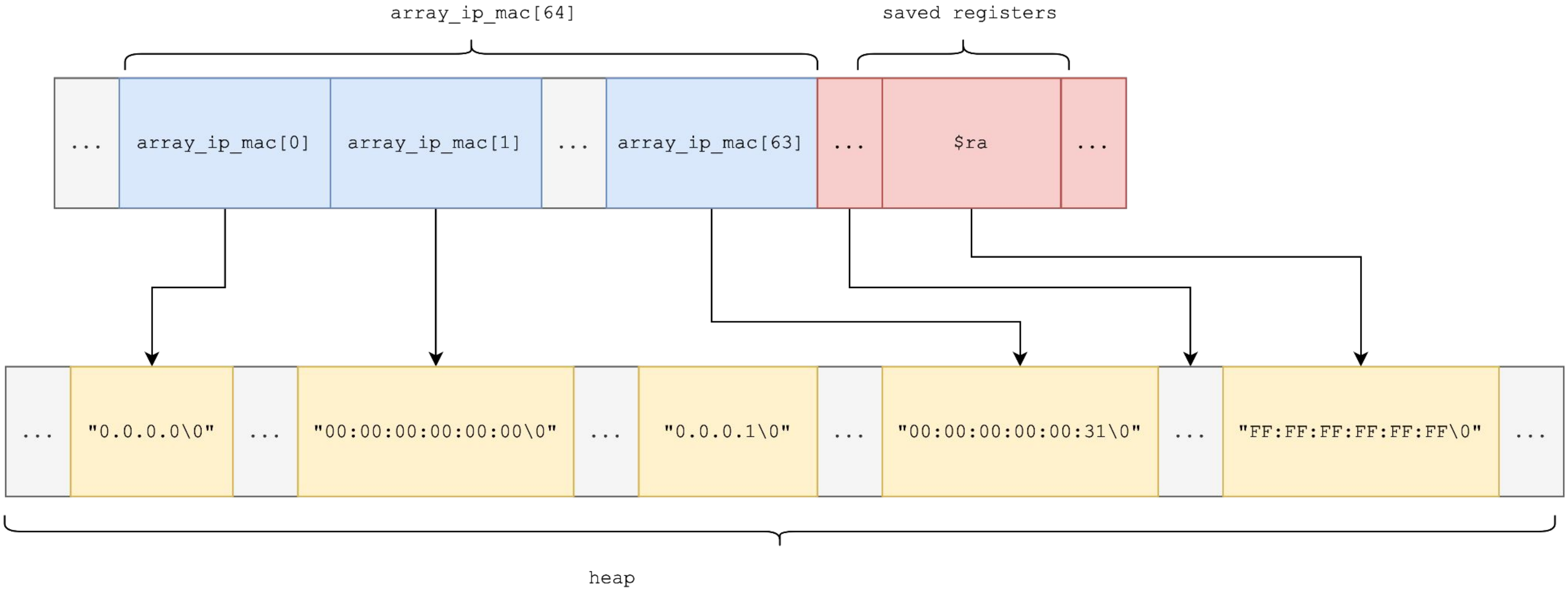
Exploitation - ASLR

- 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!
- Code execution? But devil lies in the details...

Exploitation - ASLR



Exploitation - ASLR



Exploitation - JSON encoding

- JSON checks
  - Format of MAC address is not validated, only its size (17 bytes mac)
  - But it must passes a “string” check, only `[\x20-\x7f]` is allowed
  - No more “chosen” code execution?
- ASCII Shellcoding is hard (impossible?) in this context
- Reversing a JSON parser is tedious but
  - It handles Unicode escape sequences
  - It accepts `\u00xx` for encoding any byte (except NULL bytes)
  - Shellcode without with NULLs is an acceptable constraint

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
  - Blink all the LEDs (`/sys/devices/platform/leds-gpio/leds/*/brightness`)
  - Profit \o/
- Exploit is reliable
  - Exploit takes time because `sync-server` is asynchronous and terribly slow
  - We can wait up to 80 seconds per attempt

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!

Aftermath

- To publish details, either
    - Wait for 3 months
    - OR
    - Vulnerability is patched by editor
- Patch is published
    - Analysis has been done
    - A simple counter is added
    - No more than 32 pair IP/MAC allowed, this bug is dead!
- But
    - No special hardening has been added
    - `tddp` still here…

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 ;-)
- We put everything on GitHub
  - https://github.com/synacktiv/CVE-2021-27246_Pwn2Own2020
- **Many thanks to the Barbhack organizers!**

Q&A

Thank you for your attention!

We’ll be happy to take questions :-)