

Pwn2Own'ing the TP-Link Archer A7

BARBHACK 2021

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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 organized by the Trend Micro Zero Day Initiative, 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 beforehand
- Teams order is random, duplicates are not rewarded
 - “Partial win”
- Several bugs ready but only participated in the *Routers* category

TP-Link AC1750

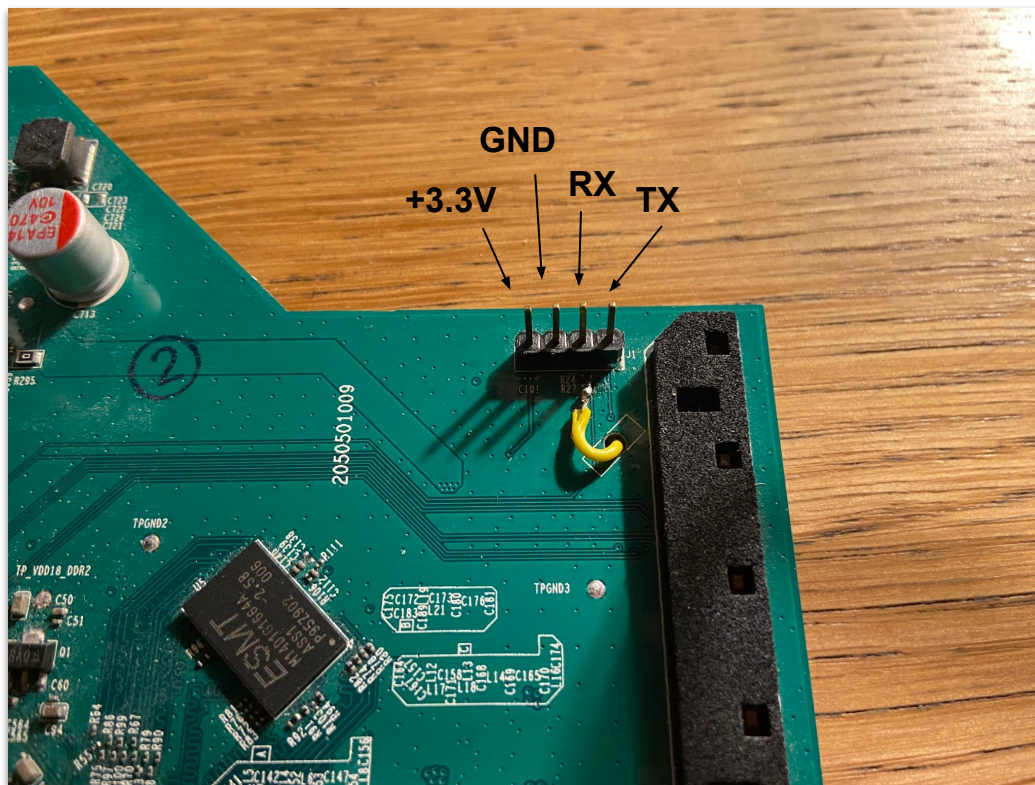
- Mid-end Wi-Fi router
- Models A7 and C7 are very similar
 - The later has Alexa support (??), mostly sold on Amazon (15k+ evaluations)
 - 720 Mhz MIPS CPU, 8MB of flash, 128MB of RAM
 - 802.11ac, 4 LAN slots + 1 WAN
- < 100€, quite popular in the custom firmware scene
 - Some documentation related 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



Initial access - UART

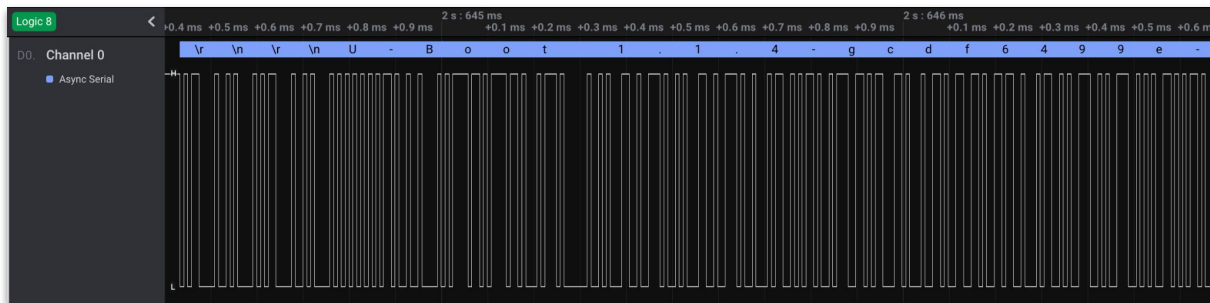
- “Free” shell access on consumer electronics is rare
- First step of any research on embedded systems
 - UART / JTAG are often easy to locate
 - Physical presence, datasheets
 - Not always restricted
 - Debugging capabilities are incredibly useful
- We won't cover the UART discovery
 - Check out Team 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



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
	<input checked="" type="checkbox"/> Show in protocol results table
	<input checked="" type="checkbox"/> 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 environment
 - 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
$MMMMM     MMMMMM     MMMMMMMMMMMMM     MMM     MMM
MMMMMMMMM  MM MMMMM.  MMMMM:MMMMMM:  MMMM  MMMMM
MMMM= MMMMM  MMM  MMMM  MMMMM  MMMM  MMMMMM  MMMM  MMMMM'
MMMM= MMMMM  MMMM  MM  MMMMM  MMMM  MMMM  MMMMMNMMMMMM
MMMM= MMMM  MMMMMM  MMMMMM  MMMM  MMMM  MMMMMMMMM
MMMM= MMMM  MMMMMM,  NMMMMMMMMM  MMMM  MMMM  MMMMMMMMMMMM
MMMM= MMMM  MMMMMM  MMMMMMMMMM  MMMM  MMMM  MMMM  MMMMMM
MMMM= MMMM  MM  MMMM  MMMM  MMMM  MMMM  MMMM  MMMM
MMMM$ ,MMMMM  MMMMM  MMMM  MMM  MMMM  MMMMMM  MMMM  MMMM
MMMMMM:     MMMMMMM  M          MMMMMMMMMMMMMM  MMMMMMMM  MMMMMMM
MMMMMM     MMMMN  M          MMMMMMMMMM  MMMM  MMMM
MMMMM      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`

```
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 function

```
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:~#
```

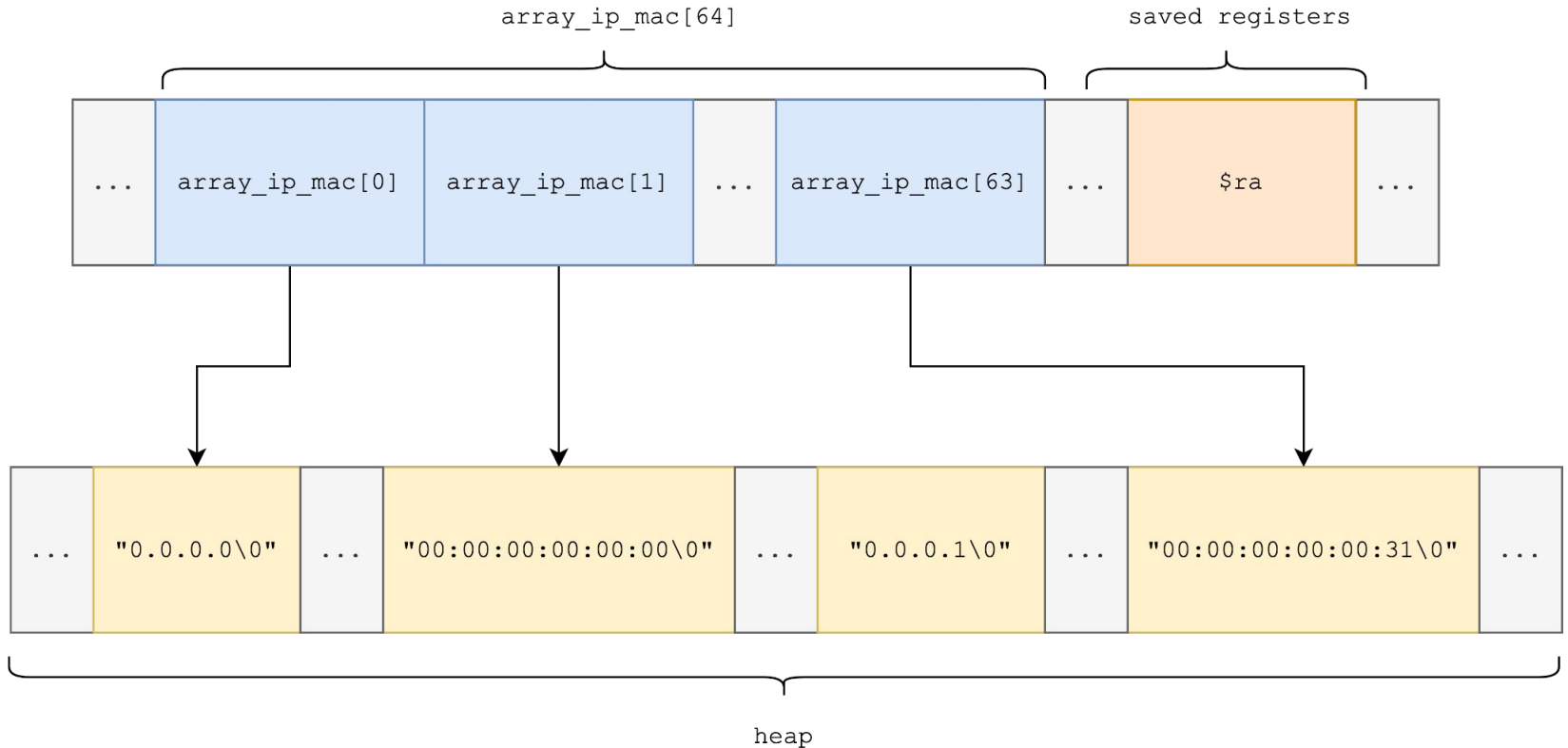
Exploitation

- 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

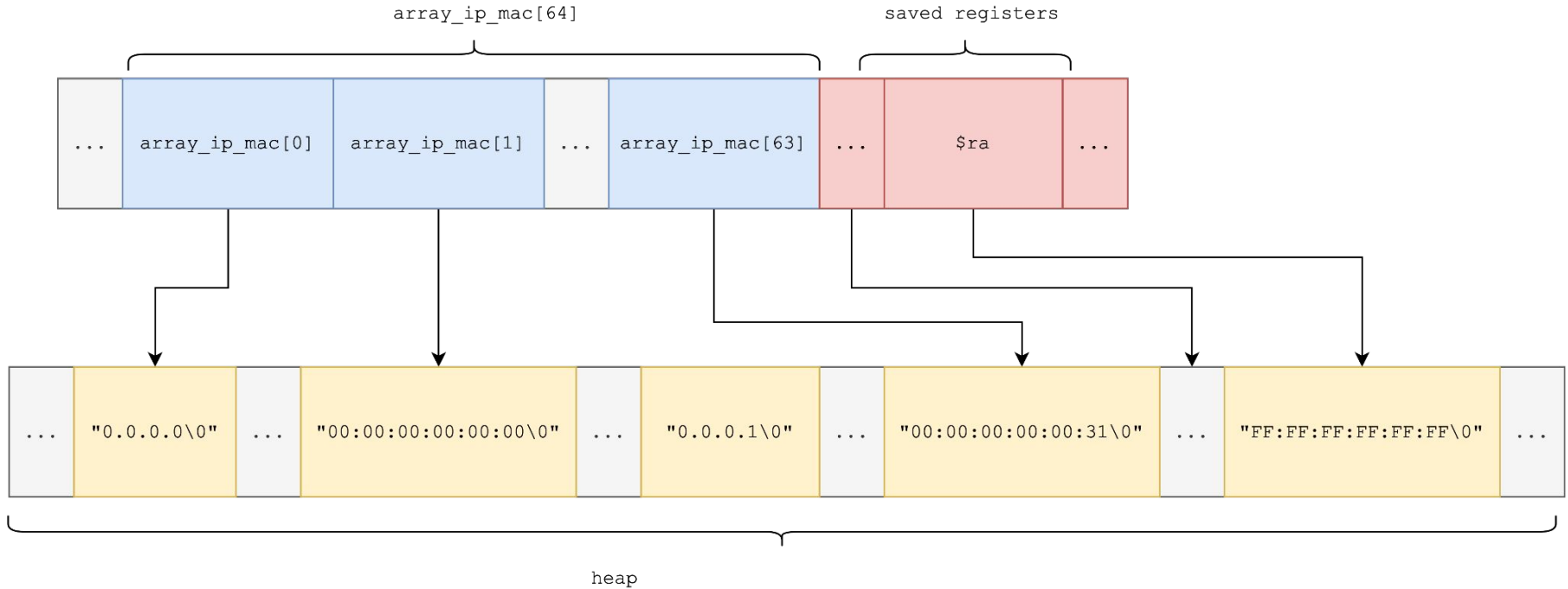
Exploitation - ASLR

- 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 pass 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 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 :-)