ESP32 Open MAC

Reversing the ESP32 Wi-Fi hardware

Jasper Devreker

esp32-open-mac.be

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The ESP32

- low cost Wi-Fi/Bluetooth microcontroller ($\sim$ €2)
- dual core
- 520 KB RAM
- FreeRTOS (real-time operating system)
- very popular with makers/engineers

Figure: ESP32 on a dev board

A bit of history

- made by Espressif
- ESP8266, released in 2014
- started out as badly documented Wi-Fi module
- got picked up by makers for its price/potential
- 10 years later, more than 1 billion chips have been produced
- almost the entire SDK is open source

Almost the entire SDK open-source?

- except for the libraries to control the Wi-Fi and Bluetooth peripherals
- provided as compiled libraries
- these abstract away the hardware and Wi-Fi stack
- example: `esp_wifi_set_mode(WIFI_MODE_STA)`

Open-source, but the source is not open

- Binary blobs are “open-source”
- as in, the blobs themselves are licensed under the Apache 2.0 license
- . . . not entirely to the spirit of open-source, but useful for us
- this grants us explicit permission to reverse engineer the code

Why?

- originally: proper 802.11s mesh networking
- auditability
- “make hardware do things it was not designed for”

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Static analysis

- Ghidra
- now has mainline support for Xtensa (thanks Austin!)
- Fortunately, Espressif did not strip function names

Decompile: mac_tx_set_plcp0 - (esp32-open-mac.elf)

```
undefined4 mac_tx_set_plcp0(int *param_1)

{
  uint uVar1;
  uint uVar2;
  uint uVar3;
  uint *puVar4;

  uVar1 = *(uint *)(*param_1 + 4) & 0xfffff;
  uVar2 = uVar1 | 0x200000;
  puVar4 = *(uint **)(*param_1 + 0x2c);
  if (((*(short *)(param_1 + 5) < 1) && ((*puVar4 & 0xc0) != 0x80)) &&
     (0xf < (byte)(*(char *)(puVar4 + 3) - 0x10U))) {
    uVar2 = uVar1 | 0x600000;
  }
  uVar1 = *puVar4;
  if (((uVar1 & 0x402) != 0) && ((uVar1 & 0x480000) != 0x400000)) {
    uVar3 = 0x3000000;
    if (((uVar1 & 0x100000) == 0) && (uVar3 = 0x2000000, (uVar1 & 0x80000) == 0)) {
      uVar3 = 0x1000000;
    }
    uVar2 = uVar2 | uVar3;
  }
  memw();
  *(uint *)((0x7fee7a4 - (uint)*(byte *)(param_1 + 1)) * 8) =
```

Dynamic analysis on real hardware

- JTAG to add breakpoints/inspect memory
- Wi-Fi dongle in monitor mode to receive all packets
- problem: lots of other Wi-Fi networks nearby

Building an affordable faraday cage

- needs to have data passthrough
- ...but powerline filter to let power in is very expensive
- solution: use fiber optics + big lead-acid battery
- `https://esp32-open-mac.be/posts/0003-faraday-cage/`
- at least 70 dB of attenuation @ 2.4GHz

Figure: Faraday cage

Dynamic analysis in emulator

- Espressif already has QEMU fork for their HW
- added support for Wi-Fi peripheral based on assumptions from static reversing
- added "execution tracing": a stacktrace is saved on every wifi peripheral access

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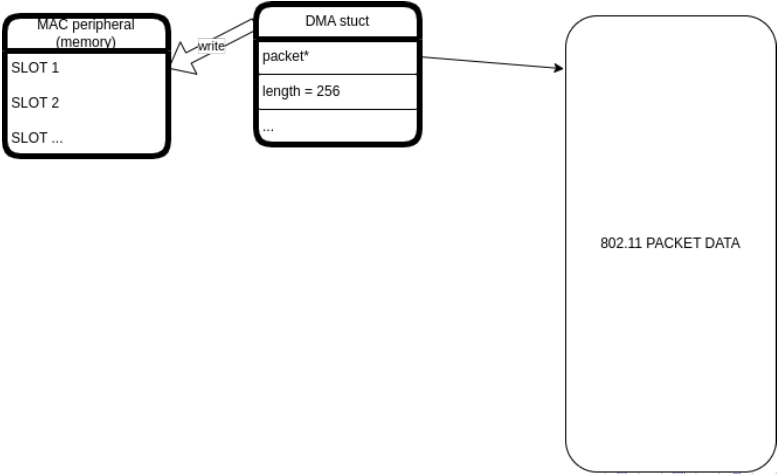
Taking over from the proprietary implementation

- let proprietary code handle entire HW initialisation
- then politely ask the FreeRTOS task to die
- replace interrupt with our own

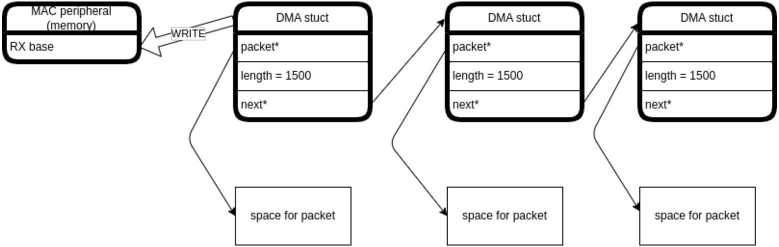
Reverse engineered TX

- DMA
- 5 TX slots
- interrupt when slot is finished with status



Reverse engineered RX

- also DMA
- chain of DMA slots
- interrupt when slot is filled in
- recycle buffers after RX



RX/TX to connect to access point

- connecting to open access point is surprisingly easy

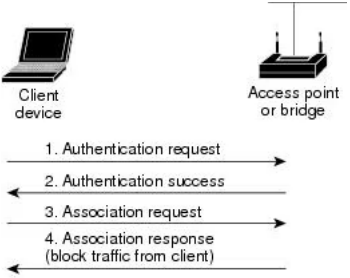


Figure: Authenticate/associate flow

Sending data to access point

- pretend we are an ethernet card (ESP-NETIF, uses LwIP under the hood)
- put packets into data frame
- we can ping the network card with only open source code running

```
64 bytes from 10.0.0.233: icmp_seq=1149 ttl=255 time=16.9 ms
64 bytes from 10.0.0.233: icmp_seq=1150 ttl=255 time=24.4 ms
64 bytes from 10.0.0.233: icmp_seq=1151 ttl=255 time=19.1 ms
64 bytes from 10.0.0.233: icmp_seq=1151 ttl=255 time=21.5 ms (DUP!)
64 bytes from 10.0.0.233: icmp_seq=1152 ttl=255 time=13.1 ms
```

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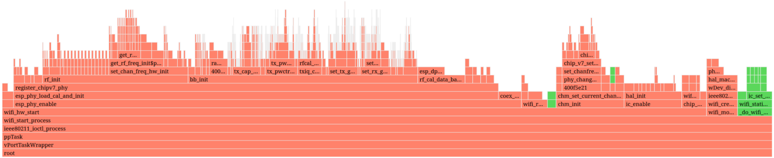
Eliminate the blobs

- “we can ping the network card with only open source code running” is a bit misleading
- proprietary code is still needed to init HW
- calibration, . . .
- very complex code



Eliminate the blobs

- current way: top-down replacement of init function
- maybe in the future: mechanical translation to C with rev.ng

Further HW reverse enineering

- 802.11n
- AMPDU, HT40, QoS
- hardware acceleration for WPA cryptography
- change channel, TX power

Adding an 802.11 MAC stack

- we can now send packets, but what packets do we send?
- PoC stack worked, but writing a whole stack is tedious
- needed for more complex actions (scanning, joining WPA2 AP, . . .)
- maybe use FreeBSD's net80211 stack

Porting to other ESP32 variants

- there are RISC-V versions of the ESP32
- those might use a completely different Wi-Fi peripheral

Bluetooth

- will likely be as much work as getting Wi-Fi to work

Thanks to!

- Simon, Antonio, Austin
- my hackerspace: Zeus WPI

Questions?

- https://esp32-open-mac.be