Unlocking the Drive

Exploiting Tesla Model 3

Who are we ?

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SYNACKTIV

- Offensive security
- 170 experts
- Pentest, reverse engineering, development, incident response

Reverse Engineering team

- 45 reversers
- Low level research, reverse engineering, vulnerability research, exploit development, etc.

Competition organized by ZDI

Took place in Vancouver (April 2023)
New Pwn2Own Automotive in Tokyo (Jan. 2024)

Pwn2Own 2022

Infotainment preauth RCE (Wifi)
& sandbox escape & 2 kernel bugs

Pwn2own 2023

Timeline

GTW
Vulnerabilities & exploit
Dec 2022

Bluetooth
Vulnerability research
Mid Jan 2023

Bluetooth
Vulnerabilities
Mid Feb 2023

Bluetooth
Finalize exploit
6 mar 2023

Exploit
A useless service
8 mar 2023

LPE
Start LPE research
13 mar 2023

PC died
on the plane
Buy a new one
20 mar 2023

Exploit
Stabilisation & chaining
20-23 mar 2023

P2O
Event
22-23 mar 2023

Car architecture

Multimedia and vehicule domains separared by a gateway

Multimedia domain

Vehicle domain

Infotainment

Connectivity components

Security Gateway

ECU 1

ECU 2

Actuators

Sensors

CAN 1

CAN N

ECU 3

Actuators

Sensors

Model 3 – Infotainment

Hardware

Gateway: SPC5748GS

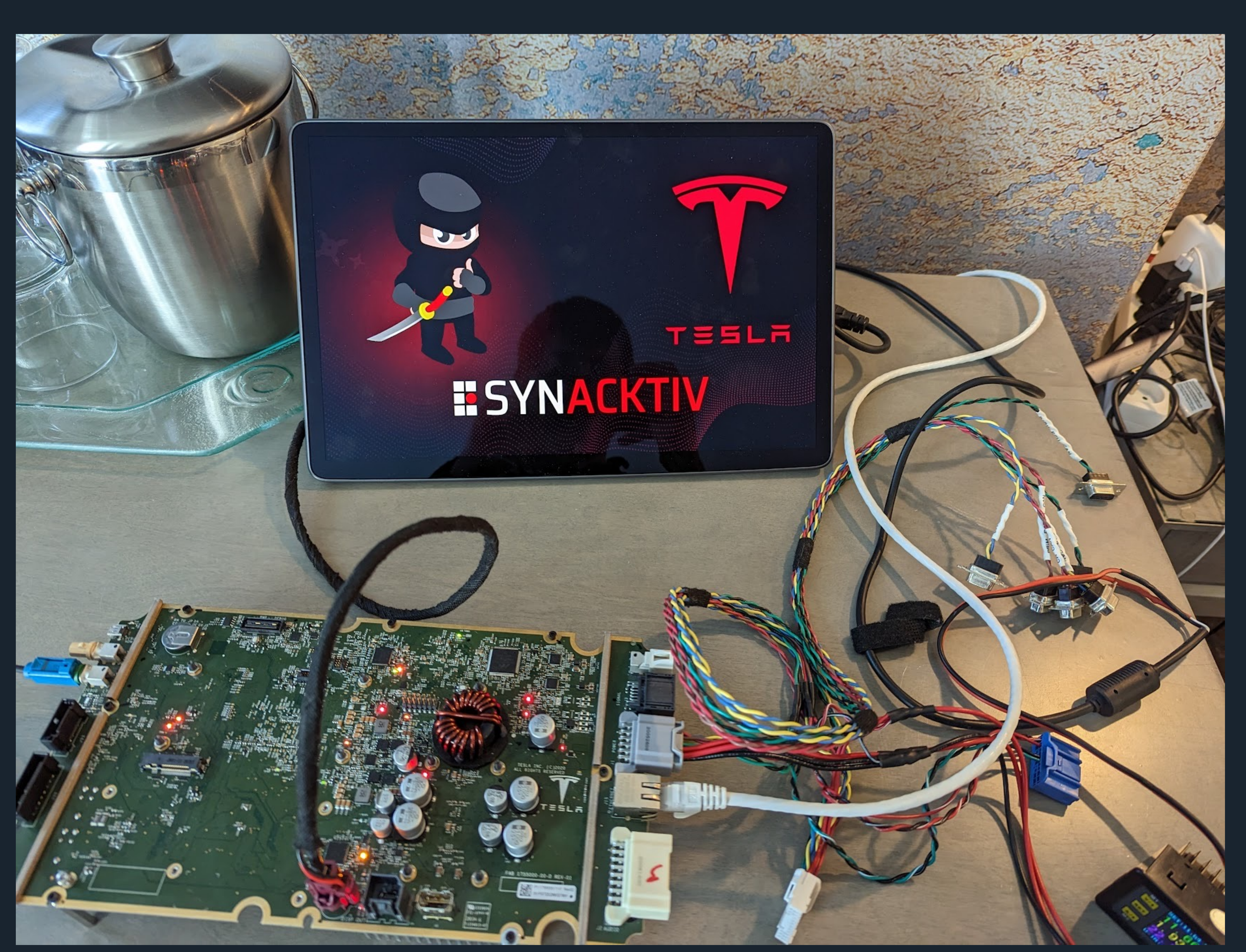
SoC Intel Atom or AMD Rizen

WiFi/BT

CANs

Hardware setup

Lab



- Multiple Infotainment ECU
  - Some from Ebay
  - 2 provided by Tesla
- After pwn2own 2022, Tesla gave us SSH keys to access our units

Exploit chain

Chaining three exploits for a remote-to-CAN fullchain

Infotainment

1

bsa_server process

Linux Userland

2

BCMDHD driver

Linux Kernel

Bluetooth Firmware

WiFi Firmware

WIFI/BT CHIP BCM4359

Attacker's PC

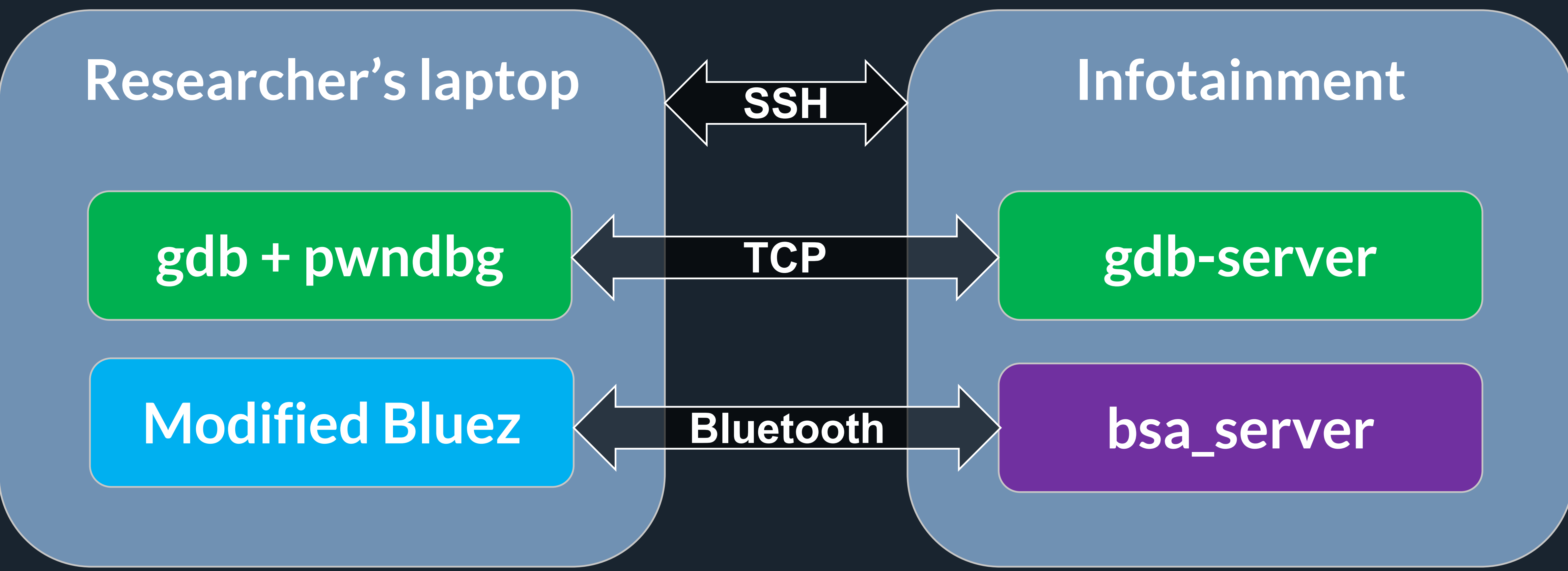
Security Gateway

3

Firmwares update app

Vulnerability research

Usual Workflow for Vulnerability research

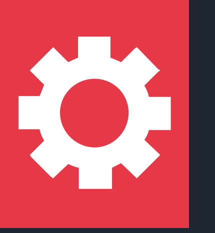


Remote GDB on physical ECU

```
*RAX  0x4141414141414141 ('AAAAAAAA')
*RBX  0x5aa672 ◂— 0x21008021007
*RCX  0xa73524 ◂— 0x1000b00111100
*RDX  0x2
 RDI  0x0
*RSI  0xc
 R8   0x0
*R9   0x7ffff7f624e0 ◂— 0x0
*R10  0x7ffff7f623e0 ◂— 0x0
 R11  0x0
*R12  0x7ffff6db8da8 —▸ 0xa73524 ◂— 0x1000b00111100
*R13  0x14
*R14  0x4d
 R15  0x0
*RBP  0xac0540 ◂— 0x201004d00004000
*RSP  0x7ffff6db8d78 —▸ 0x414ef2 ◂— movzx eax, byte ptr [rbx + 1]
*RIP  0x417264 ◂— jmp rax
 ► 0x417264    jmp    rax                          <0x4141414141414141>
```

Static analysis

- Reverse engineering with Ghidra / IDA
- Help of debug symbols from another binary

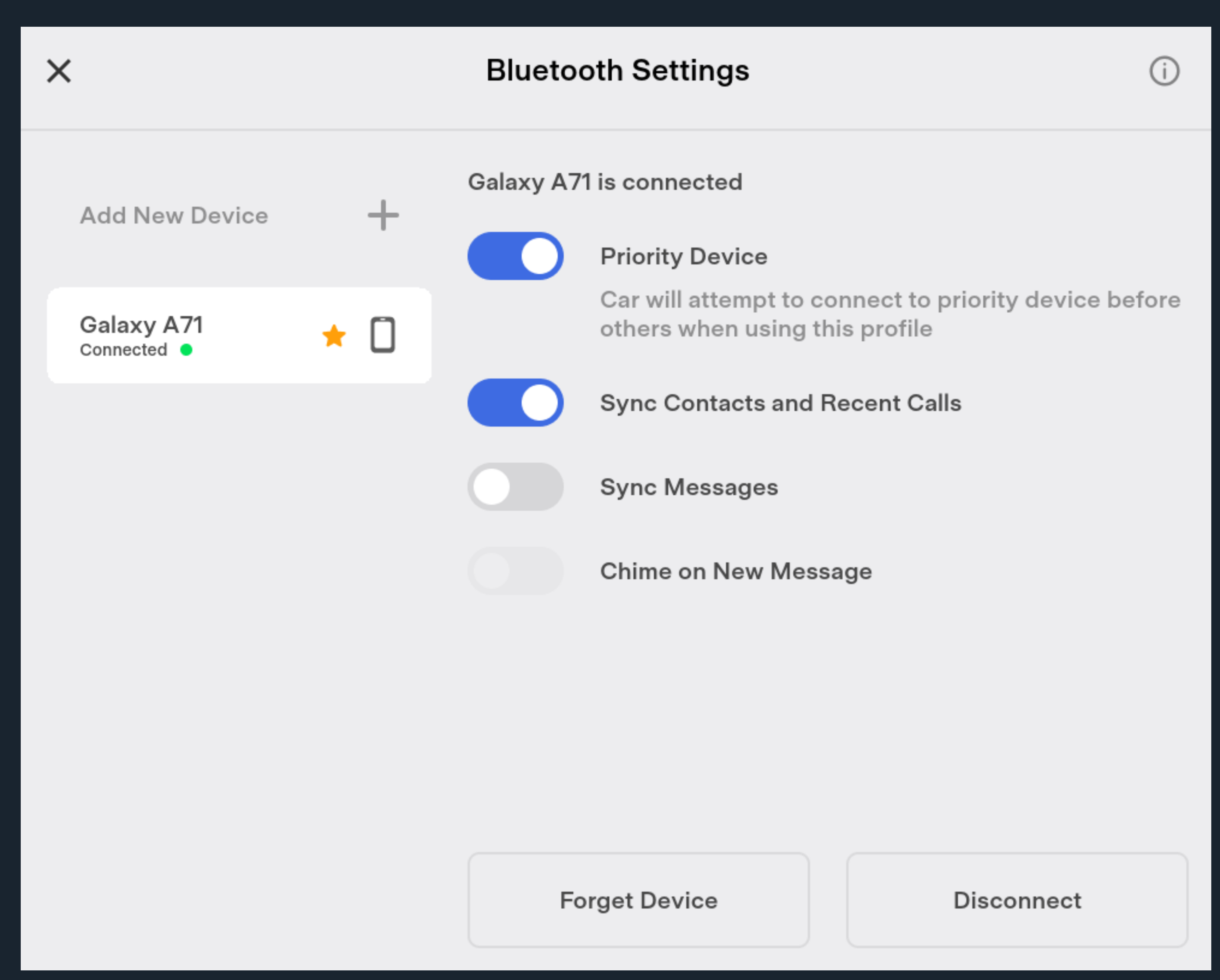


Dynamic instrumentation

- Attacker device is a laptop with a standard bluetooth chip
- Bluez recompiled to add our exploit code
- Tesla Infotainment with SSH access and gdb

Bluetooth features

Why does the car need Bluetooth ?



Message and contact synchro.

Display received messages on the infotainment screen

Voice call

Compose and receive calls

Play music

Play music from a phone using Bluetooth standards (supported by smartphones)

Spotify

Play music from a phone using Spotify

Bluetooth stack

Implementation in the infotainment

Wifi / BT Chip

UART

Infotainment kernel

UART subsystem

TTY

chardev

Infotainment userland

bsa_server

UNIX

btd

DBUS

Qtcar-bluetooth

HCI

Whole Bluetooth stack

bsa-server

Custom Bluetooth stack

Big attack surface

A lot of bluetooth features are managed by this program

High probability of vulnerability

Closed source vendor code written in C

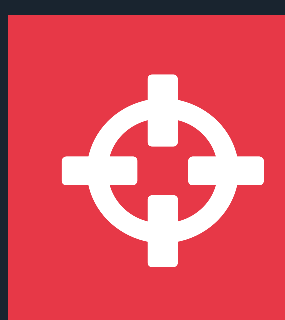
Custom allocator

Bad hardening

Binary compiled without PIE

Debug symbols

Similar binary with debug symbols found on Github



Natural target for an attacker

Looks like an exception in this heavily hardened system

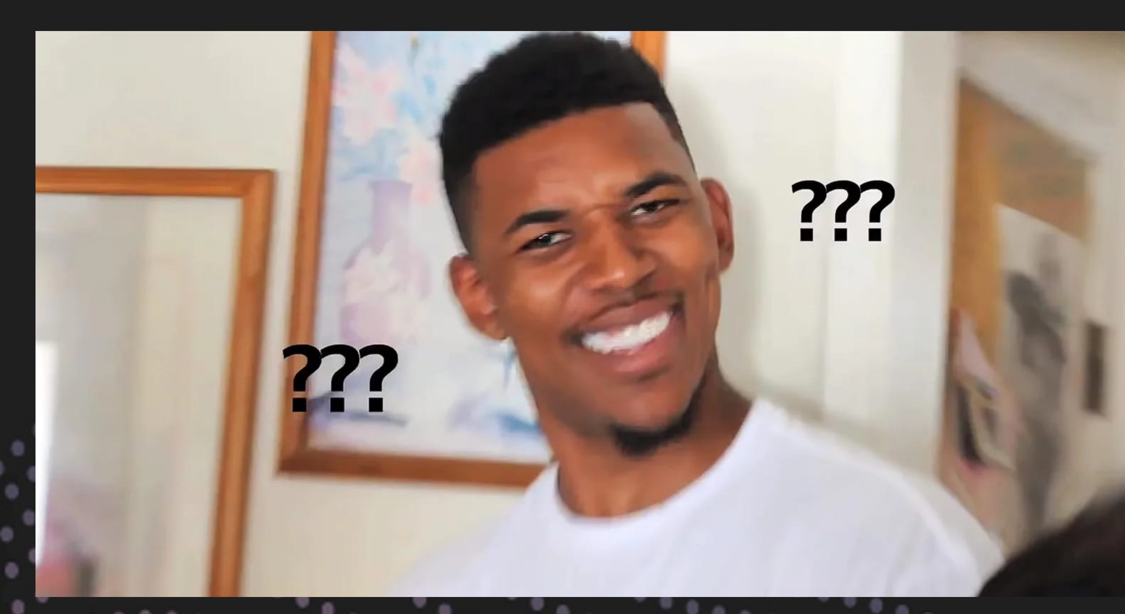
Sandboxes

The process is still well sandboxed

Bluetooth classic

A huge attack surface

SPP GATT MAP AVRCP SDP PAN AVDTP HID L2CAP SYNC RFCOMM DUN OBEX HCI BNEP HFP FTP



All these acronyms are real Bluetooth protocols / profiles

And there are **much** more…

Bluetooth classic

Attack surface on Tesla car

PROFILES

OBEX

SDP

RFCOMM

L2CAP

HCI

Hardware / RF

Profiles for Audio Playback

Service Discovery (SDP)

Retrieves the service list provided by the peer

Advanced Audio Distribution Profile (A2DP)

Protocol for audio streaming

Audio/Video Remote Control Profile (AVRCP)

Audio controls (play/stop, playlist management, ...)

Basic Imaging (BIP)

Allows to transfer the Cover Art image

Reaching the BIP surface

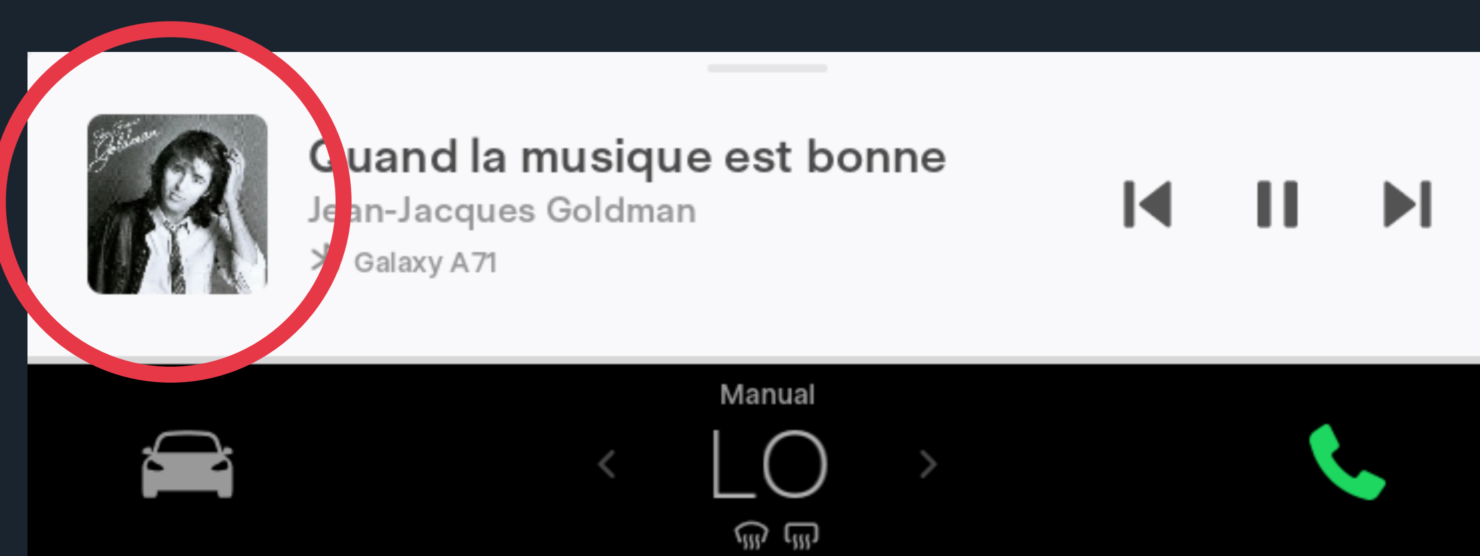
1. **Playback is configured by the phone (AVRC)**
2. **The car queries available Cover Art pictures** using OBEX protocol
3. **The phone send available images description** using OBEX protocol
4. **The car downloads and displays one image**

OBEX GET x-bt/img-img

```
<image-descriptor version='1.0'>…</image-descriptor>
```

OBEX Response

```
<?xml version='1.0' encoding='utf-8' standalone='yes' ?>
<image-properties>
…
</image-properties>
```



Vulnerability in BIP

OOB Write

Heap buffer overflow in the BIP protocol implementation

- In the BIP parsing function (bip_xp_parse)
- Parsing result is stored in an allocation of 0x2800 bytes containing an array of images metadata
- Adding an « attachment » fills 0x100 bytes, 38 are enough to overflow (limit is 256, due to a bug)
- Allows writing controlled bytes after the end of an allocation (custom allocator)

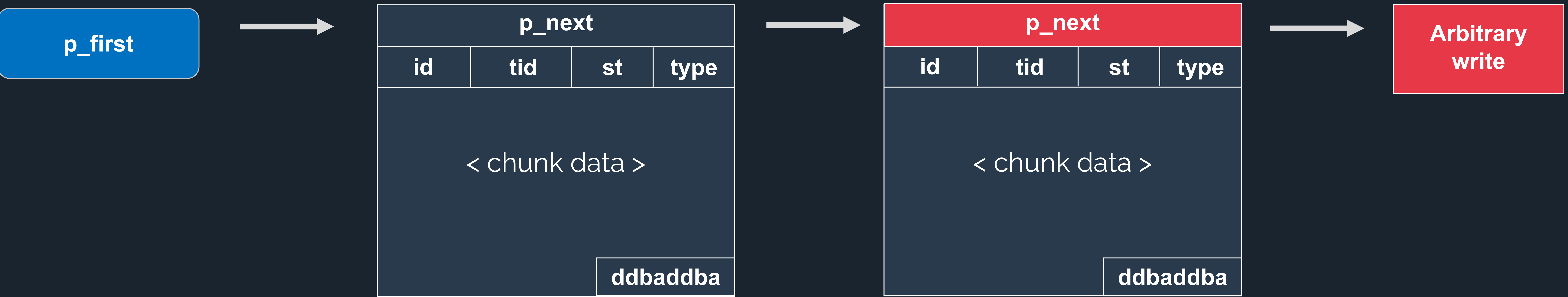
```
<?xml version='1.0' encoding='utf-8' standalone='yes' ?>
<image-properties>
<attachment />
<attachment />
<attachment />
...
<attachment name="AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA" />
</image-properties>
```

Heap exploitation

Bsa-server custom heap

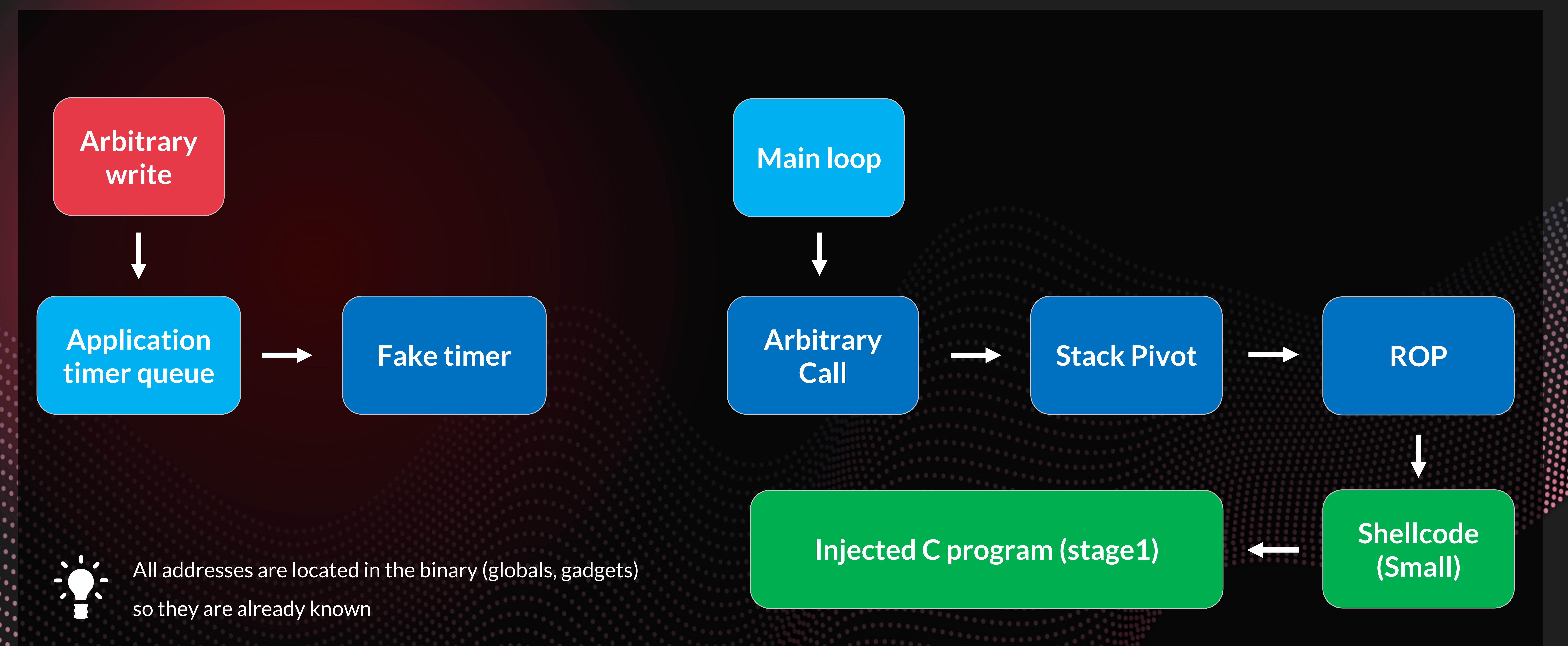
Custom heap management from a code base called GKI

- Allocations located in arrays in the data section (no PIE = no ASLR)
- Very few corruption checks compared to the glibc



Code execution

Taking over a timer, again…



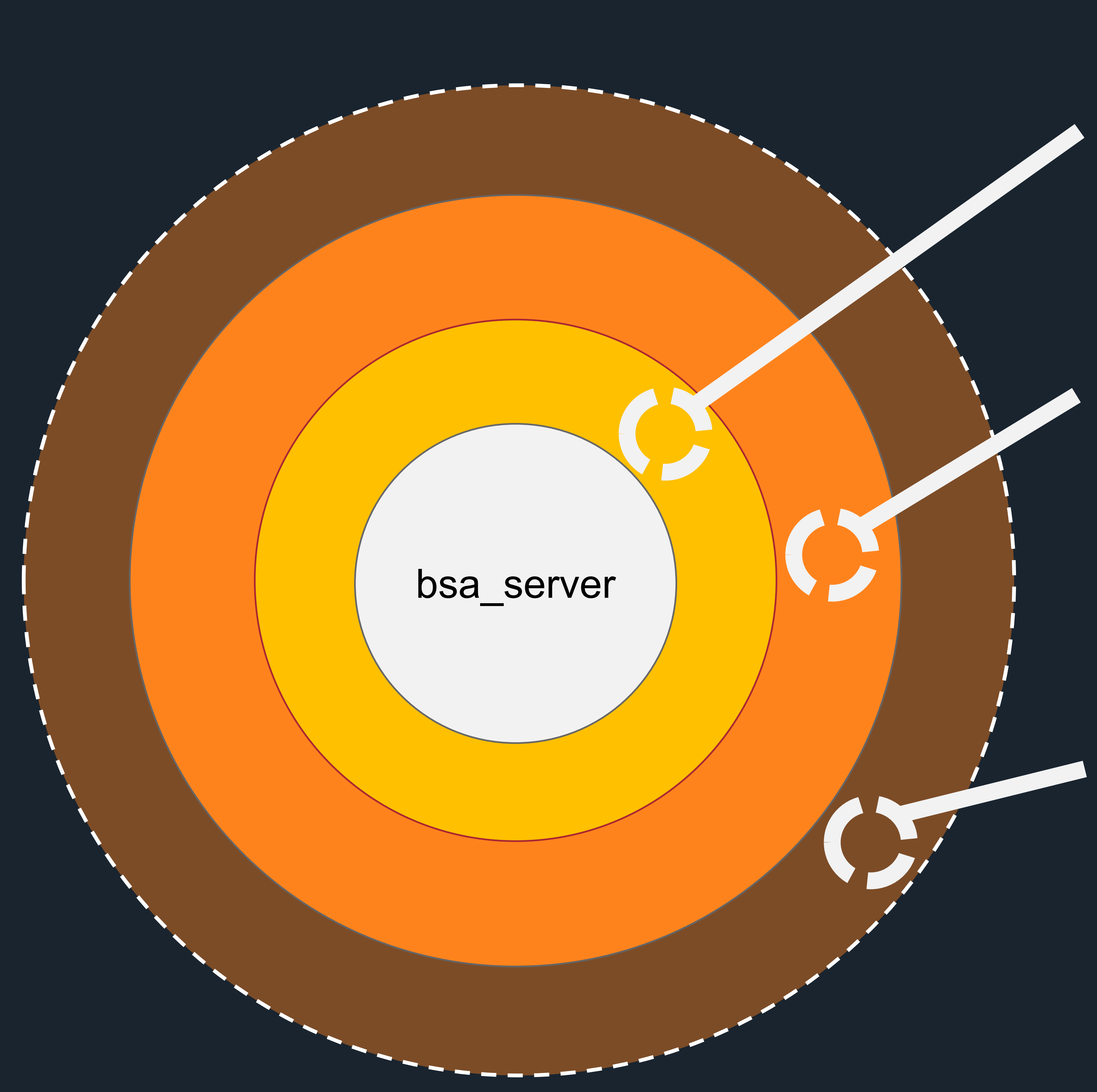
The end ?

What can we do with this code execution ?

- Dedicated UID
- No useful capability
- No network
- All sandboxes activated

- But two legitimate APIs
  - TTY communication
  - One UNIX socket to communicate with btd

➢ Limited attack surface



Kafel

- Syscalls filtering

AppArmor

- Whitelist for file access
- Cannot execute anything

Minijail

- Dedicated chroot
- Empty network stack

LPE

Arbitrary write inside the chipset firmware

Infotainment

bsa_server process

Stage1 payload

HCI

Linux Userland

BCMDHD driver

Linux Kernel

Bluetooth Firmware

WiFi Firmware

WIFI/BT CHIP BCM4359

- bsa_server communicates with Bluetooth chipset through HCI protocol
- Vendor specific commands are used to initialize the chipset (i.e. load Bluetooth firmware patches)
- At least HCI_BRCM_WRITE_RAM and HCI_BRCM_SUPER_PEEK_POKE commands allow arbitrary writting to the internal chipset memory
- So stage1 injected in bsa_server can write inside the chipset memory

LPE

Gaining code execution inside the WiFi chipset

Infotainment

bsa_server process

Stage1 payload

Linux Userland

HCI

BCMDHD driver

Linux Kernel

Bluetooth Firmware

WiFi Firmware

Shared memory

Stage2 payload

- Bluetooth firmware and WiFi firmware share some memory regions
- WiFi firmware RAM code is mapped at address 0x500000 in the Bluetooth part
- HCI_BRCM_WRITE_RAM HCI command allows writing to the WiFi firmware RAM code
- WiFi firmware runs on an ARM core
- So stage1 injected in bsa_server can patch WiFi firmware to inject custom code
- WiFi Firmware Idle task is patched to jump on the injected code: stage2

LPE

Code execution inside the WiFi chipset

```c
void hcibt_write_payload(struct hcibt* bt)
{
    uint32_t i;
    uint32_t *payload = (uint32_t *)&bin_payload_bin[0];
    for(i=0; i<(bin_payload_bin_len/4)+1; i++) {
        write_u32(bt, 0x01DE42C + 0x500000 + i*4, payload[i]);
    }
}
void hcibt_jump_payload(struct hcibt* bt)
{
    write_u32(bt, 0x189780 + 0x500000, 0xfe54f054); // idle thread, bl payload
}
```

Stage1 WiFi code injector

```
ROM:0018977C
ROM:0018977C                      idle_thread                          ; CODE XREF: idle_thread_entry+4↓j
ROM:0018977C 10 B5                             PUSH        {R4,LR}
ROM:0018977E 04 46                             MOV         R4, R0
ROM:00189780
ROM:00189780                      loc_189780                           ; CODE XREF: idle_thread+E↓j
ROM:00189780 54 F0 54 FE                       BL          injected_code ; Keypatch modified this from:
ROM:00189780                                                           ;   BL threadx_idle_enter
ROM:00189784 20 46                             MOV         R0, R4
ROM:00189786 99 F6 FF F8                       BL          0x22988 ; hnd_poll
ROM:0018978A F9 E7                             B           loc_189780
ROM:0018978A                      ; End of function idle_thread
```

Patched WiFi Firmware idle_thread to jump in stage2

LPE

Attack surface from the chipset

Infotainment

bsa_server process

Stage1 payload

Linux Userland

BCMDHD driver

Linux Kernel

PCIe

Bluetooth Firmware

WiFi F Stage2 payload

WIFI/BT CHIP BCM4359

- WiFi part of the chipset uses PCIe to communicate with the main processor
  - DMA
  - Mailbox
- WiFi is managed by the BCMDHD Linux driver
- Stage2 in the WiFi firmware is well placed to attack the Linux driver

LPE

Bcmdhd to chipset memory structures

```
typedef struct ring_info {
    uint32      ringmem_ptr; /* ring mem location in dongle memory */

    /* Following arrays are indexed using h2dring_idx and d2hring_idx, and not
     * by a ringid.
     */

    /* 32bit ptr to arrays of WR or RD indices for all rings in dongle memory */
    uint32      h2d_w_idx_ptr; /* Array of all H2D ring's WR indices */
    uint32      h2d_r_idx_ptr; /* Array of all H2D ring's RD indices */
    uint32      d2h_w_idx_ptr; /* Array of all D2H ring's WR indices */
    uint32      d2h_r_idx_ptr; /* Array of all D2H ring's RD indices */

    /* PCIE_DMA_INDEX feature: Dongle uses mem2mem DMA to sync arrays in host.
     * Host may directly fetch WR and RD indices from these host-side arrays.
     *
     * 64bit ptr to arrays of WR or RD indices for all rings in host memory.
     */
    sh_addr_t   h2d_w_idx_hostaddr; /* Array of all H2D ring's WR indices */
    sh_addr_t   h2d_r_idx_hostaddr; /* Array of all H2D ring's RD indices */
    sh_addr_t   d2h_w_idx_hostaddr; /* Array of all D2H ring's WR indices */
    sh_addr_t   d2h_r_idx_hostaddr; /* Array of all D2H ring's RD indices */

    uint16      max_sub_queues; /* maximum number of H2D rings: common + flow */
    uint16      rsvd;
} ring_info_t;
```

- Some structures are shared between chipset and driver, like pciedev_shared_t / ring_info_t
- These structures are reloaded from the chipset memory while handling a mailbox interrupt
  - In normal operation: during chipset startup, and chipset software crash
- Stage2 can generate the mailbox interrupt to fill the structure ring_info_t

LPE

Out-of-bound write in bcmdhd

- d2h_r_idx_ptr is used as an offset to write inside a ioremap region (TCM)
- The offset is not checked to be in the TCM region!
- Ioremap places addresses in the vmalloc region
- Stage2 can write out of bound after the ioremap TCM region by setting d2h_r_idx_ptr to a value bigger than the TCM size
- Need to find something to write on!

TCM ioremap buffer

LPE

Out-of-bound write exploitation

- Process Kernel Stacks are good candidates

  - Are in vmalloc region (allocated in _do_fork function)
  - Can be sprayed from Stage1 by forking process multiple times
  - Process children can be blocked in a syscall to stay in Kernel (i.e. clock_nanosleep)
  - Write to Process Kernel Stacks is a powerful primitive => **direct ROP** after unblocking syscall

- Thanks to a big buffer allocated by the GPU driver, the offset (from TCM) of a process kernel stack is fixed

- Stage2 (payload in WiFi firmware) can patch a process kernel stack of a child of Stage1 (payload in bsa_server) blocked in clock_nanosleep

KASLR bypass

& hardened kernel configuration ☹

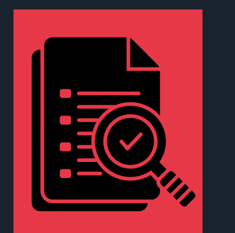
Random kernel base address
But not a lot of possibilities…

0xffffffff81000000
0xffffffff82000000
0xffffffff83000000
…
0xffffffffbf000000

Reading a nice blogpost on side-channels at the same time…

EntryBleed: Breaking KASLR under KPTI with Prefetch (CVE-2022-4543)

https://www.willsroot.io/2022/12/entrybleed.html



Similar side-channel issue
Prefetch times differ

ffffffffb0900000 179
ffffffffb0a00000 138
ffffffffb0b00000 136
ffffffffb0c00000 44
…
ffffffffb1300000 179

ROP chain

End of a kernel process stack

```
0xffffc90024007f50 | 75 00 a0 81 ff ff ff ff 44 44 44 44 44 44 44 44 |
0xffffc90024007f60 | 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 |
0xffffc90024007f70 | 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 |
0xffffc90024007f80 | 44 44 44 44 44 44 44 44 42 02 00 00 00 00 00 00 |
0xffffc90024007f90 | 00 00 00 00 00 00 00 00 44 44 44 44 44 44 44 44 |
0xffffc90024007fa0 | 44 44 44 44 44 44 44 44 da ff ff ff ff ff ff ff |
0xffffc90024007fb0 | b1 d2 23 92 c0 55 00 00 c0 ed 63 db ff 7f 00 00 |
0xffffc90024007fc0 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 |
0xffffc90024007fd0 | e6 00 00 00 00 00 00 00 b1 d2 23 92 c0 55 00 00 |
0xffffc90024007fe0 | 33 00 00 00 00 00 00 00 42 02 00 00 00 00 00 00 |
0xffffc90024007ff0 | 80 ec 63 db ff 7f 00 00 2b 00 00 00 00 00 00 00 |
```

Last return address

Some controllable saved task registers (used to restore register values)

Strategy

Pivot

1. Replace Return address by a RET gadget address (**that is executed when the clock_nanosleep syscall ends**)
2. Use saved register as a first ROP chain

Ropchain 1 (in saved registers)

1. Jump in **copy_from_user** to fill the Kernel process stack with a second ROP chain

Ropchain 2

1. Jump in **copy_from_user** to override **poweroff_cmd** string in the kernel memory with the command we want to start
2. Call **poweroff_work_func** to start the command as root with User Mode Helper Linux subsystem
3. Call **do_exit** to end the task properly

Infotainment

bsa_server process

Stage1 payload

Stage3
Executed as root
from the kernel

Linux Userland

BCMDHD driver

Linux Kernel

Bluetooth Firmware

WiFi F

Stage2 payload

WIFI/BT CHIP BCM4359

```
$ ./demo
```

LPE

root code execution

Infotainment

bsa_server process

Stage1 payload

Stage3
Executed as root
from the kernel

ETHERNET

Linux Userland

BCMDHD driver

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Bluetooth Firmware

WiFi F

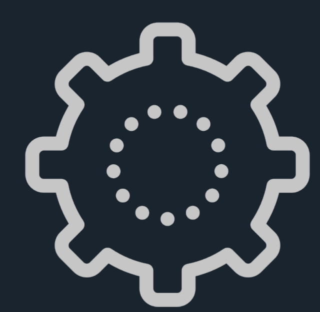
Stage2 payload

WIFI/BT CHIP BCM4359

Security Gateway

GTW

Security Gateway architecture



SYSTEM

Same PCB as Infotainment

—

SoC NXP MCP5748G

—

FreeRTOS PPC-VLE

—

No hardware based secure-boot

—

Uses its own internal flash for software

NETWORKS

Ethernet

—

CAN buses (Chassis/Party/Vehicle)

Features

Filter CAN messages

—

Save log files

—

Update mode
Update other ECUs and itself

—

Provide sensitive information to other ECU
(VIN/Serial/…)

—

Config Ethernet switch

GTW

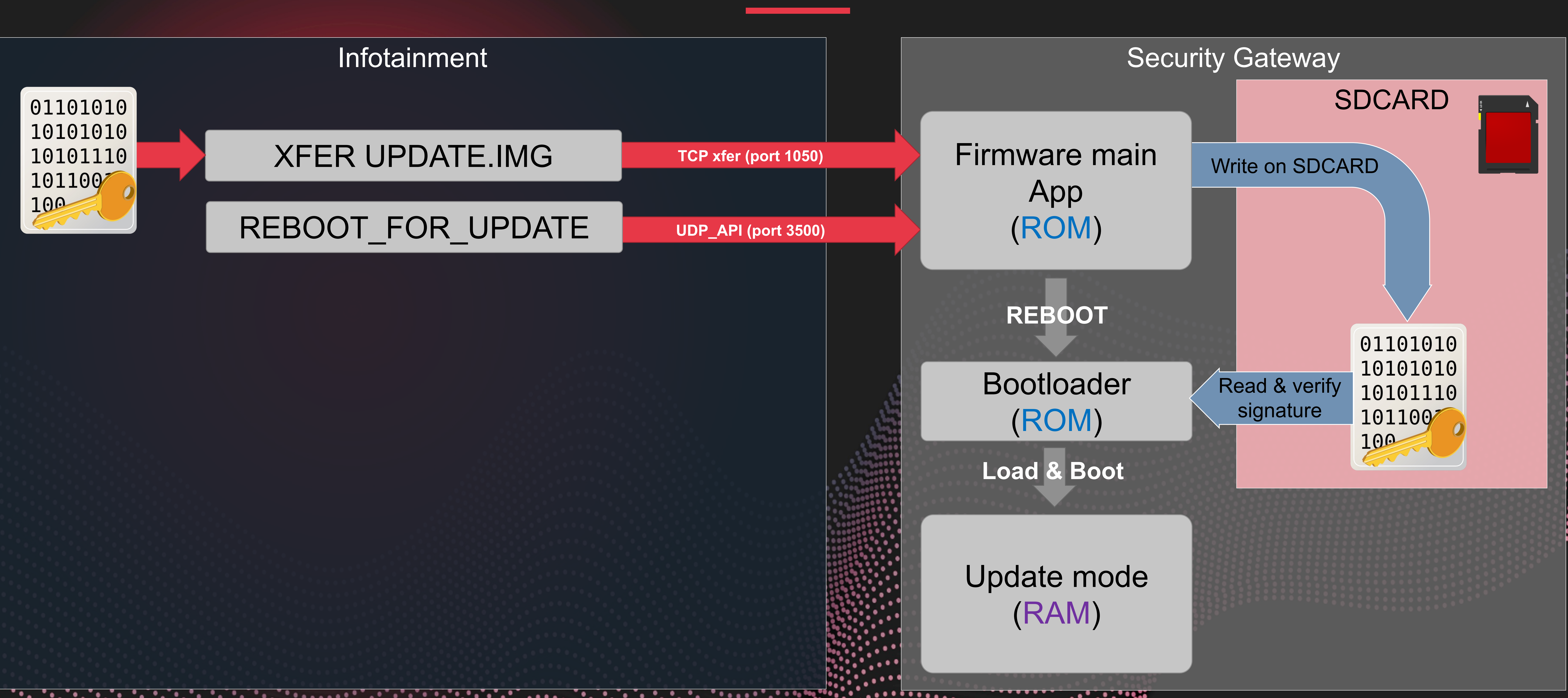
Security Gateway software & attack surface

- 3 main software parts
  - Bootloader
    - Selects between the two following modes and do software secure boot
  - Update mode
    - Fetches updates on the infotainment through TFTP
    - Checks them and updates ECUs through CAN
  - Main App mode
    - Handles CAN over UDP messages and filters them
    - Provides access to some sensitive values (VIN, autopilot subscriptions etc..)
    - Acts as a log server

- GTW uses fixed addresses (no ASLR, code is in the internal flash)
- Seems to be greatly audited, and safely developed
- Logic TOCTOU bug inside the update mode => 100% stable

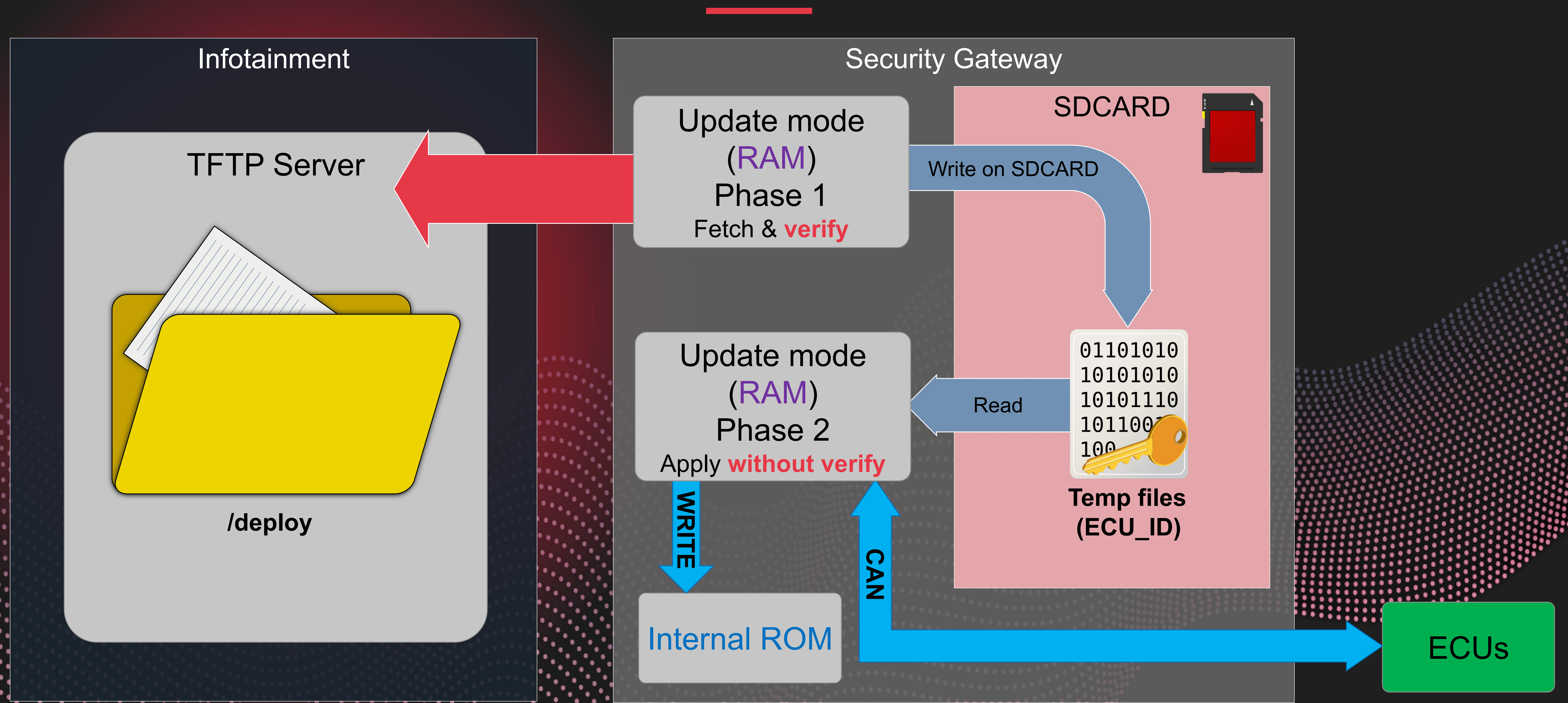
GTW

Booting the update mode



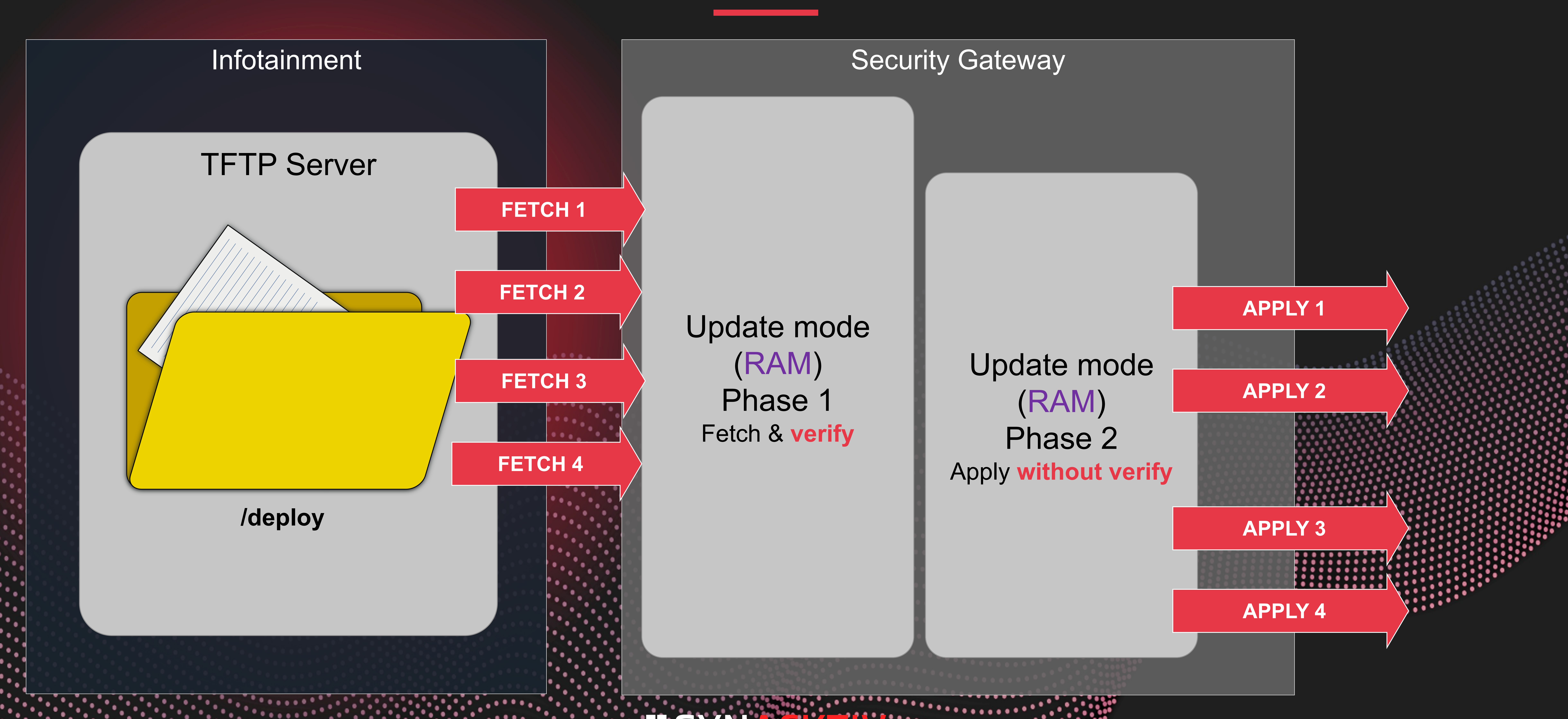
GTW

Update mode interactions



GTW

Update mode two phase mode



- Update mode can be forced to fetch two times the same ECU update
- The first time if the file has a good signature the update is scheduled to be applied, and the file is saved on the SDCARD
- The second fetch overrides the file on the SDCARD, if the signature is invalid the first one is still scheduled, and the bad temporary file is not removed
- When applying updates, the signature is not re-checked, so the badly signed file is applied
- This bypasses the signature check, and allows an attacker to apply arbitrary updates, and can be used to gain code execution on the security gateway

Security Gateway

Bootloader
(ROM)

SDCARD / FAT32 driver | TFTP client | Internal Flash

ED25519 Signature verification

Update mode (sdcard -> RAM) | Update mode (TFTP -> RAM) | App Mode (ROM)

- Bootloader verifies next stages
- Hardware (NXP chip) doesn't provide secure boot, bootloader in the internal flash is never verified
- Gateway update mode allows to update its own firmware, including the bootloader
- Signature bypass in update mode => code exec in bootloader

Security Gateway

Bootloader
(ROM)

SDCARD / FAT32 driver | TFTP client | Internal Flash

ED25519 ~~signature~~ verification

Update mode (sdcard -> RAM) | Update mode (TFTP -> RAM) | App Mode (ROM)

- Bootloader patch
- Remove ED25519 signature check
- Use Update mode boot mechanism to boot on a controlled firmware
- Controlled firmware has unrestricted access to the CAN vehicle & chassis buses

Access to CAN busses

From remote to CAN

Infotainment

bsa_server process

Stage1 payload

Stage3
Executed as root
from the kernel

Linux Userland

BCMDHD driver

Linux Kernel

Bluetooth Firmware

WiFi F

Stage2 payload

WIFI/BT CHIP BCM4359

ETHERNET

Security Gateway

Stage4
Custom firmware

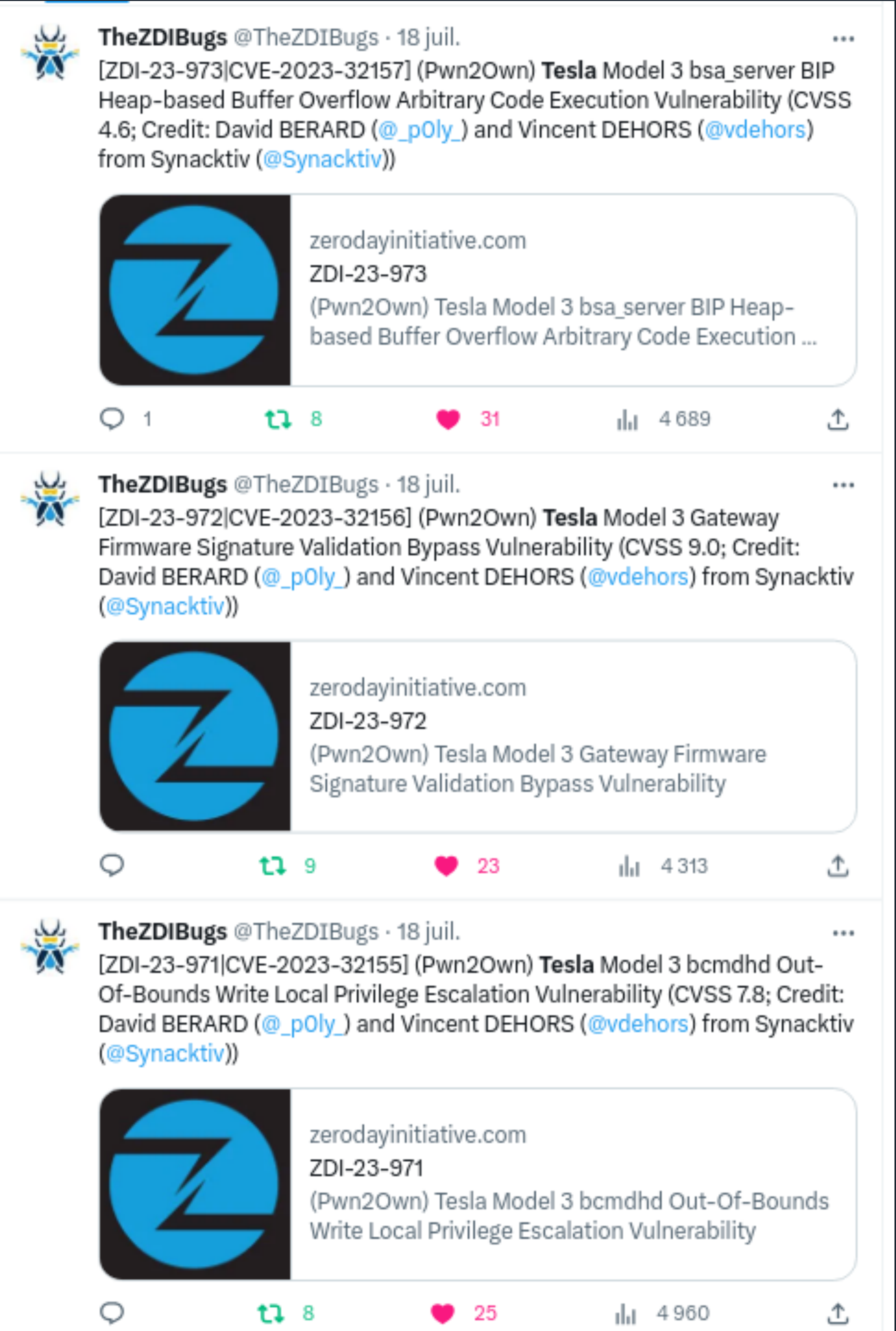
CAN

ECUs

Fixes

Tesla Response

- bsa_server is now a PIE binary and the vulnerability has been patched
- Bcmdhd vulnerability is patched
- Security GTW
  - Now moves files with a specific name when signature is correct
  - Manifest is now signed
  - If a signature check fails, the file is deleted from the SDcard



Pwn2Own 2023

Synacktiv was Master Of Pwn for the second time with many entries (Windows/macOS/Ubuntu/VirtualBox/Tesla)

First Tier 2 entry ever (could have been a Tier 1 but we had chosen to split RCE+LPE and Gateway entries)

Conclusion

- **Not so long of a work**
  - Strong knowledge of the Tesla cars architecture (Pwn2Own 2022)
  - Hardware and debug facilities
  - Not well hardened binary
- **Great support from Tesla**
  - Tesla provided us an ECU that can receive updates
  - ZDI and Tesla gave us updates
  - Version freeze 1 month before the event
  - **Thanks to them**
- **Was fun**
- **We won a car for our future research ☺**

SYNACKTIV

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