SYNACKTIV

GreHack 8-bit_edition

No lightsaber is needed to break the Wookey

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Who are we ?

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- Security researcher @Synacktiv
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Synacktiv

- Offensive security company
- Based in France
- ~70 Ninjas
- We are hiring !!!

Introduction

CESTI Challenge

- Organized every two years to evaluate ITSEF/CESTI laboratories
- Until this year :
  - Two challenges were organized, one for hardware CESTIs, and one for software CESTIs
  - CESTIs have different products to evaluate depending on their agreement categories.
- This year a unique challenge has been organized on a unique product
  - The objective is to evaluate software laboratories to do hardware testing and vice versa
  - Common target : **Wookey**

Wookey

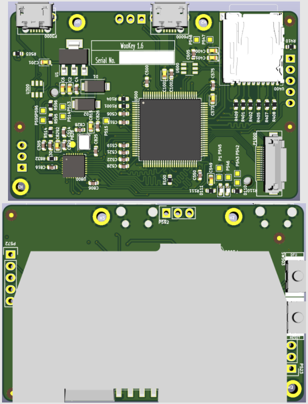
What is Wookey

- Open-Source and Open-hardware
- Developed by ANSSI
- Secure USB storage device
  - Encrypted data on an SD card
  - Authentication through a touchscreen
  - Double authentication : PET & User PIN
- Multiple smartcards are used for cryptographic operations
  - User smartcard for authentication and data decryption
  - DFU smartcard to enter in update mode
  - Firmware signature
- Firmware is unique per device (contains encrypted secrets)

Wookey : Hardware

Hardware design

- Main MCU : STM32F4
  - JTAG only on debug boards
  - Production boards rely on Read Out Protection (RDP=2) to disable JTAG
  - MPU used for the multitask OS
- Used interfaces
  - SPI for the display
  - ISO7816 to communicate with the smartcard
  - Buttons for DFU mode and reset
  - USB HS/LS for USB Mass Storage
  - UART for logs (may be used as input on debug board)



Wookey : Software

Developers

- Full software stack developed by ANSSI and available on Github

Languages

- Bootloader : C
- Micro-Kernel : ADA
- Drivers and Task : C

OS

- Cortex-m4 MPU is used to isolate tasks
- Syscalls are handled by the ADA Micro-Kernel
- Task and drivers have permissions that are verified by the kernel in syscalls

Challenge Scope

Methodology

1. CESTI asked to write a full test plan
2. ANSSI reviewed test plan and selected few tests (hardware and software)
3. CESTI do their analysis based on selected tests
   - 3 boards were given to CESTIs : prod board, dev board, STM32F4 discovery
4. CESTI write their assessment report and send it to ANSSI
5. ANSSI will organize a debriefing session with all CESTIs

Synacktiv selected tests

- SW : ADA kernel syscalls analysis and fuzzing
- SW : Fuzzing of the ISO7816 library which handles smartcard messages
- HW : Review of the secure channel establishment
- HW : Analysis of the RDP2 protection (used to disable JTAG) regarding its resistance to power glitches

Software : Syscall fuzzing

Very basic Syscall fuzzer

- On a development board
- Syscall fuzzer is built inside a userland task
- Choose a random syscall number
- Choose argument values in a list that contains
  - random values
  - limit values
  - valid pointer pointing to random data
  - …
- Collect result on the UART : kernel crash logs on it (even on the production boards)

```
FUZZER      syscall 12 (SVC_IPC_RECV_SYNC) ..
FUZZER            arg0 = 0xb1da0a40
FUZZER            arg1 = 0x20006290
FUZZER            arg2 = 0x0
FUZZER            arg3 = 0x20006290
FUZZER
Frame 1000BEC4
EXC_RETURN FFFFFFF1
R0   2
R1   0
R2   94
R3   0
R4   2
R5   1000061C
R6   0
R7   20006290
R8   B1DA0A40
R9   1
R10  94
R11  20005FD0
R12  0
PC   80219CE
LR   80214BD
PSR  100000B
panic: Hard fault!
```

Software : Syscall fuzzing

Results

- Quickly got multiple crashes on multiple syscalls
- One of them allows writing a zero (32bits) at an arbitrary address !
- Trivial exploit
  - `MPU_CTRL` register is memory mapped and allows to disable the MPU
  - MPU is the only feature used to isolate task memory
  - Without MPU, tasks can read and write the kernel

```
EXPLOIT     MPU_CTRL is @ 0xe000ed94
EXPLOIT     Writing 0...
EXPLOIT     MPU should be turned off !
EXPLOIT     Looking for tasks @ 0x10000000
EXPLOIT     struct task is @ 0x100006e0
EXPLOIT      name = EXPLOIT
EXPLOIT      entry_point = 0x8090001
EXPLOIT      ttype = TASK_TYPE_USER
EXPLOIT     control = 0x3
EXPLOIT     setting to ttype = TASK_TYPE_KERNEL
EXPLOIT     control = 0x2
EXPLOIT     Privileged mode !
```

Software : Syscall review

Code review

- ADA is not so easy to read for people not familiar with it (like us).
- Some low impact bugs found

Results

- ADA protect you from basic memory bugs, but for a OS kernel the same bug classes as C can be present
- Use of `ada.unchecked_conversion` have to be double-checked
- Fuzzer found bugs we didn't find during code audit.

Software : lib7816 fuzzing

Coverage guided fuzzing

- C library
- Easy to make it standalone
- Parse smartcard messages on a X64 PC
- Libfuzzer + ASAN

Result

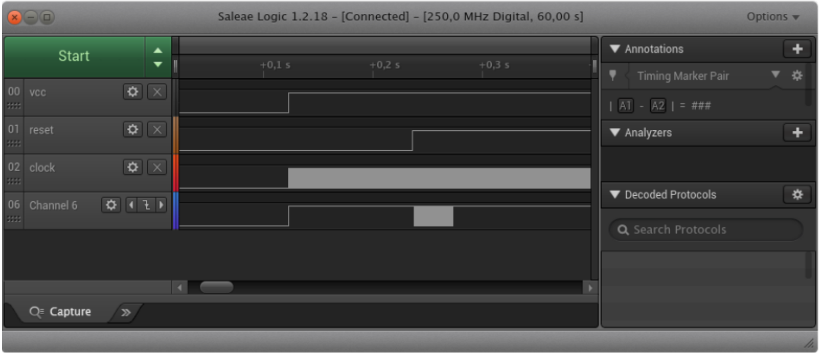
- Good coverage
- No bug found
- Studing this library was helpful for hardware tests.

Hardware : Secure channel

Decoding ISO7816 frames

- Logic analyzer to capture traffic from/to the smartcard
- Modification of the ISO7816 Saleae decoder to add a PCAP export
- Custom Wireshark dissector to parse Wookey specific frames

Hardware : Secure channel



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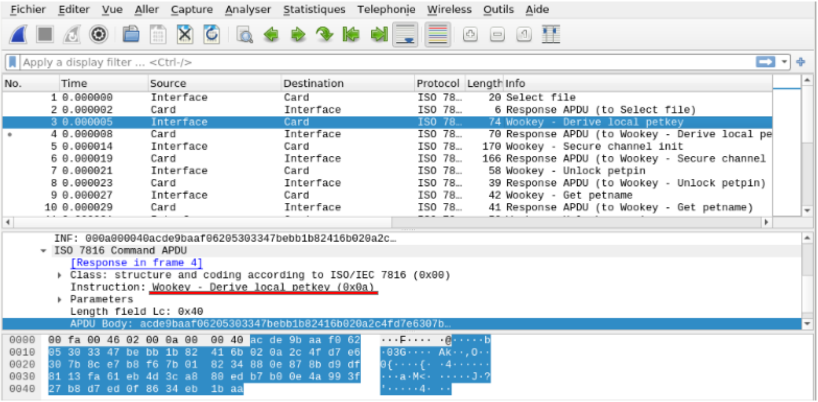
Hardware : Secure channel



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Hardware : RDP

STM32 Read Out Protection

- STM32 Debug functionalities can be limited/disabled with this protection
- RDP configuration is saved in options bytes
- 1 byte for 3 different states :
  - RDP0 : **0xAA** No protection (default), JTAG is enabled
  - RDP2 : **0xCC** All debug features are disabled, no JTAG
  - RDP1 : **All other values** : Flash memory is protected against reading
- No downgrade possible from RDP2

STM32 Read Out Protection : Fault attack

- Many public research on the subject on STM32F1, STM32F2 and STM32F3 (power glitches, EM, laser)
- Downgrade from RDP2 to RDP1 by injecting fault during the BootROM startup
- A single bit flip when BootROM reads RDP option byte allows the downgrade
  - RDP1 state is coded with many values
- A public research show how the RDP1 state can be bypassed

Hardware : RDP

STM32 Read Out Protection : Wookey

- Wookey uses RDP2 to disable all debug features
- Wookey developers are aware of these vulnerabilities, the bootloader contains mitigations
  - Double checks are implemented in critical places
  - RDP value is read by the bootloader and checked with 0xCC (RDP2)
- In case of anomaly detection **tasks are erased from the flash**
- Our objective : fault Wookey's STM32F4 RDP with a single fault with cheap hardware

Hardware : Power glitches setup

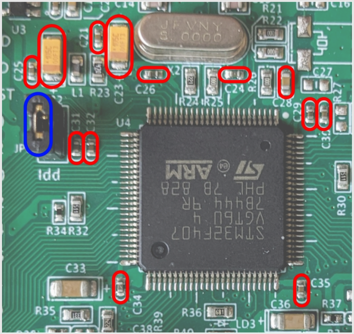
Board selection

- The Wookey board should not be modified
- Wookey project can be built for STM32F4 discovery board
- Discovery boards are not expensive, we can risk to break some
- Full schematics are available online

Hardware : Power glitches setup

External MCU power supply

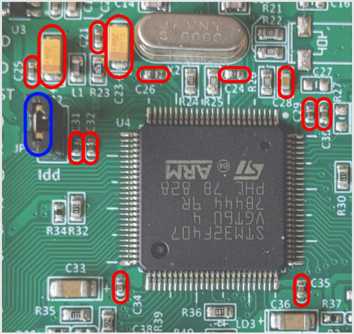
- To inject power glitches power supply must be finely controlled
- On discovery board a jumper can be removed to place an ampere meter (in blue)
  - Can be used to isolate the board internal power supply
  - External power supply can be connected on these PINs
- Reset PIN is available on headers

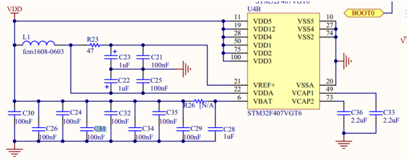


Hardware : Power glitches setup

removing Decoupling capacitors

- To inject power glitches power supply must be finely controlled
- Decoupling capacitors are here to stabilize MCU power supply
- Fault will be injected with power pulses
- Decoupling capacitors absorb such rapid power changes
- Unsolder them! (in red)

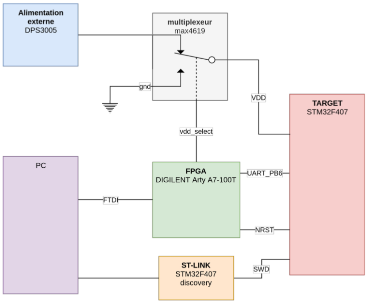




Hardware : Power glitches setup

Test bench

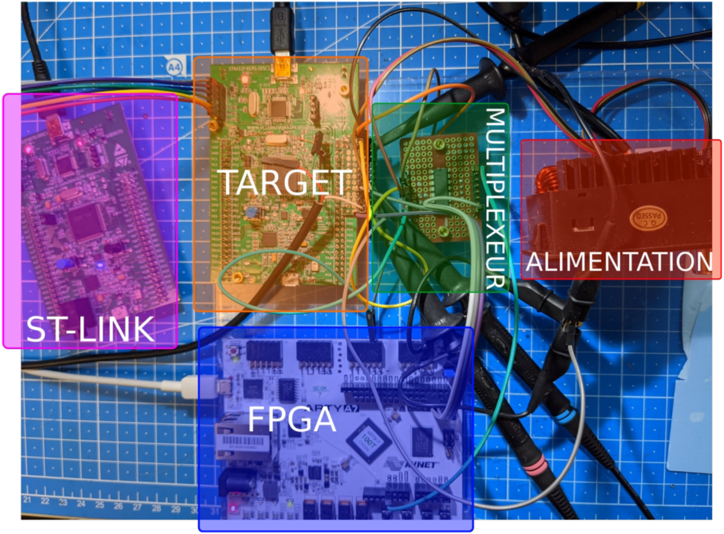
- **External power** : DPS3005 ~30€
- **Multiplexer** : MAX4619 ~1€
- **FPGA** : Arty A7-100T ~200€
- **SWD probe** : Another STM32F4 discovery board



FPGA

- Drive multiplexer to switch from external power to ground
- Forward Wookey's UART logs to the PC
- Drive Wookey RST to reboot board

Hardware : Power glitches setup



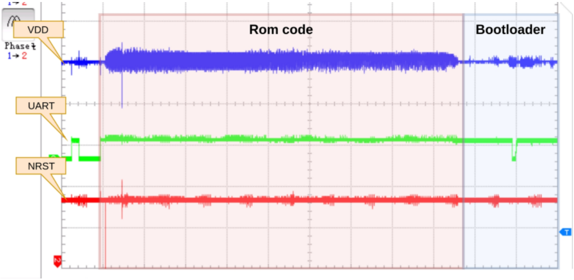
Hardware : Fault injection, pulse generation

Pulse parameters

1. PC sends **width** and **delay** parameters to the FPGA (counted in FPGA cycle : 1ns)
2. FPGA toggles RST
3. FPGA waits **delay** cycles
4. FPGA toggles multiplexer control PIN : MCU power is now connected to ground
5. FPGA waits **width** cycles
6. FPGA toggles multiplexer control PIN : MCU power is now reconnected to power supply
7. PC tries a JTAG connection

PC collects UART logs during all these operations

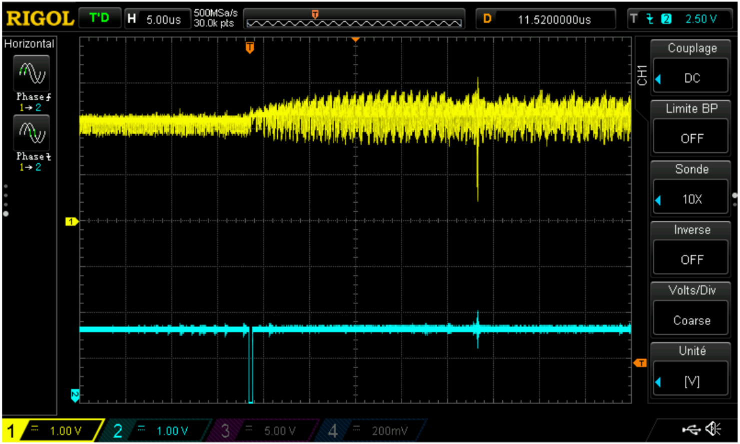
Hardware : Fault injection, parameters



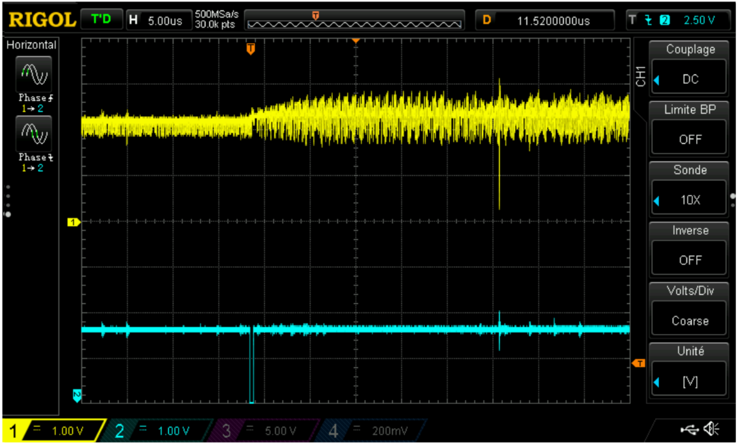
Find correct fault parameters

- Try all combinations of **width** and **delay**
- Width : 1 to 15 FPGA cycles
  - MCU doesn't survive if glitches are more than 15 cycles wide
- Delay : 0 to 52 000 cycles
  - Easy to spot the bootloader initialization by looking at the UART

Hardware : Fault injection, parameters



Hardware : Fault injection, parameters



Hardware : Fault injection, collect data

On each try

- Try JTAG connection
- Collect bootloader logs for futur analysis

```
======= Wookey Loader ========
Built date    : Dec 19 2019 at 08:52:29
Board         : STM32F407
RDP_value     : 0xcc
==============================
Hard fault
  scb.hfsr 40000000  scb.cfsr 100
-- registers (frame at 20001f74, EXC_RETURN
  r0  500000c       r1  80       r2  7b
  r4  0       r5  8000188  r6  0  r7  ca0c
  r8  0       r9  0  r10 0  r11 0
  r12 0       pc  2035c30  lr 8003025
-- stack trace
  20001f70: 8003973  0  8000188  0
  20001f80: ca0c  0  0  0
  20001f90: 0  fffffff9  500000c  80
  20001fa0: 7b  500000c  0  8003025
  20001fb0: 2035c30  0  20001fc0  800123d
  20001fc0: 0  3000003  0  c
  20001fd0: 3  fc0ca3f3  20001fe0  80012e3
  20001fe0: 1  3000003  20001ff0  80012ff
Oops! Kernel panic!
```

Hardware : Fault injection, results

RDP downgrade : Results

- Wookey protections are resistant
- Bootloader detects RDP inconsistency
- Erase sensitive data and reboot the board

Bootloader glitches

- Many glitches detected in UART log
  - PANIC
  - Values modification
  - State machine state changes
- Replaying parameters (**glitch + delay**) give a good reproduction rate
- Only the bootloader has protections
- **Other software components can also be targeted**

Hardware : Fault injection, enlarge your scope

libiso7816

- Already analyzed / fuzzed, no vulnerabilities found
- Handle smartcard messages before user authentication
- Rapid source code review to find a place where a glitch can create a software vulnerability

Hardware : Fault injection, smartcard library

```
atr->h_num = atr->t0 & 0x0f;
for(i = 0; i < atr->h_num; i++){
        if(SC_getc_timeout(&(atr->h[i]), WT_wait_time)){
                goto err;
        }
        checksum ^= atr->h[i];
}
```

Answer To Reset message

- ATR is the first message from the smartcard after reset
- Parsed by libiso7816

ATR parsing

- `atr->h` is a 16 bytes long stack buffer
- `atr->t0` value comes from the smartcard
- If a glitch affects `h_num` value a stack-overflow can occur

Hardware : Fault injection, smartcard library

```
loc_80C4306
LDRB     R3, [atr,#1]
LDR.W    curr_mask, =(SC_current_sc_frequency - 0x80C4324)
AND.W    R3, R3, #0xF
MOV      R9, #0xFFFFFFEE
STRB.W   R3, [atr,#0x26]
ADD.W    R6, atr, #0x12
SUB.W    R9, R9, atr
ADD      R10, PC             ; SC_current_sc_frequency
```

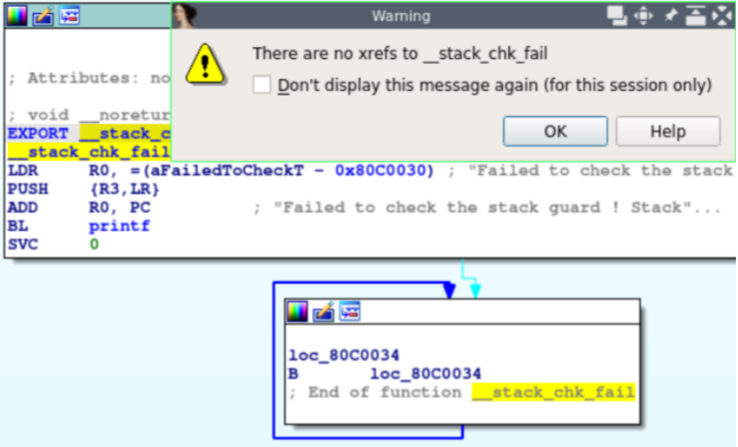
Stack-Overflow

- `h_num` is computed from masked `atr->t0` with a single instruction
- Glitching this instruction will cause the usgaeo of a non-masked value, and leads to overflow

OK! but Wookey has stack cookies!

- Are you sure?

Hardware : Fault injection, smartcard library



Stack cookie code present, but not used

Hardware : Fault injection, smartcard library

```
config STACK_PROT_FLAG
        bool "Activate -fstack-protection-strong"
        default y
...
config STACKPROTFLAGS
        string
        default "-fstack-protector-strong"
        depends on STACK_PROT_FLAGS
```

Typo in the build chain

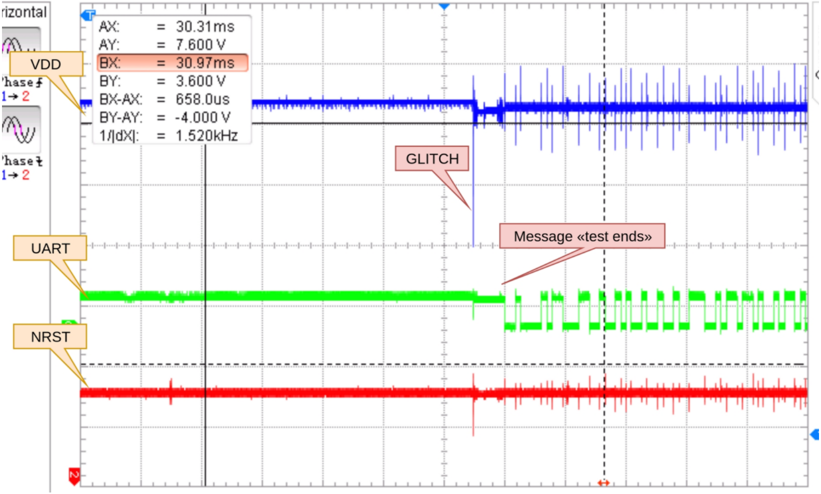
Hardware : Fault injection, PoC

```
void glitch_me() {
    char buffer[16] = {0};
    int size = 0;

    size = src_buffer[0] & 0x0F;
    memcpy(buffer, src_buffer, size);
}
int _main(uint32_t my_id) {
    // [...]
    printf ("init done.\n");
    glitch_me();
    printf("test ends\n");
```

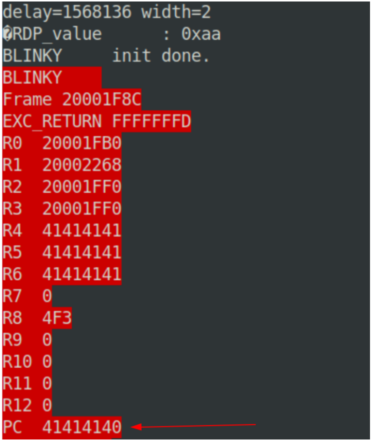
- Patch the `BLINKY` demo task to add similar code
- Produce same assembly code for masking length
- UART logs `init done.` and `test ends` help to identify the temporal range to target

Hardware : Fault injection, PoC



Hardware : Fault injection, PoC

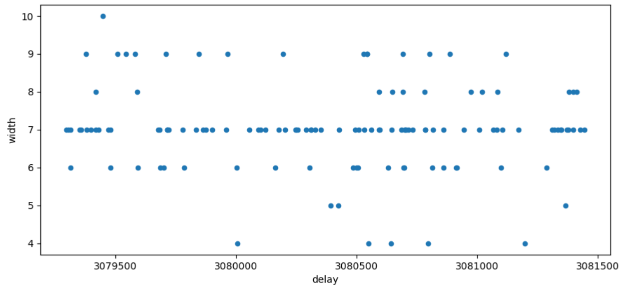
- Try all **delay** values in the targeted temporal range
- Expect `test ends` message on the UART
- Collect UART logs
- Got some `PC = 0x41414140` :-)



Hardware : Fault injection, PoC

Low reproduction rate

- Targeted code is after bootloader, OS initialization, many hardware interactions, etc.
- Execution of the targeted instruction is not stable
- Can be improved : 7 FPGA cycle look to be the optimal **width** value



Successful glitches parameters

Hardware : Fault injection, PoC

On the real device

- This research has only been done on the discovery board
- Attack on real devices require to implement smartcard protocol in the glitch setup
- Fault injection can be synchronized with ISO7816 frames to improve the reproduction rate

Conclusion : Impacts

On the device

- Glitch on the smartcard library allows gaining code execution
- Can be chained with the EoP (syscall bug) to gain privileged code execution

Scenario

- Clone, by injecting dumped encrypted secret in a new Wookey
- Modify firmware, privileged code can alter flash data

Conclusion : Impacts

Encrypted data

- Wookey design relies on smartcard for cryptographic operations
- Gaining code execution before user authentication does not allow decrypting data
- Complex attack scenarios (clone, steal and modify) can be used by an attacker to gain access to decrypted data

QUESTIONS ?

THANK YOU FOR YOUR ATTENTION

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