TRAITOR : a multi clock-glitch attack platform reproducing EMI effects at low-cost.

par **Ludovic Claudepierre**

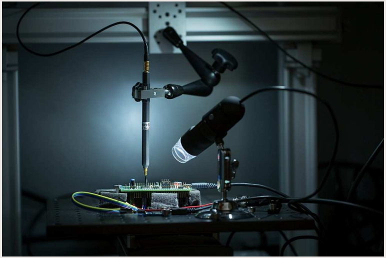
Plan

Hacking IoT with Fault attack

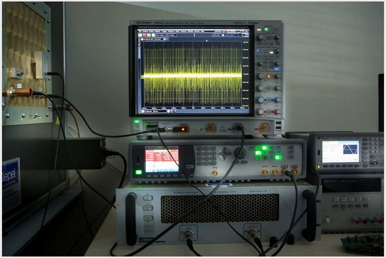
- Fault attack : runtime modification of the firmware
- Applications : retrieve a crypto-key, bypass any security mechanism
- Main difficulty : microcontroller is a black-box

Plan

Faustine



Inside the Faraday cage : magnetic probe in the close vicinity of the targeted chip



Waveform generation :

- Delay generator
- Signal generator
- Amplifier

Capability of EMI

Virtual NOP by modifying OPCODE *[Moro et al. 2013]*

- Random change of the OPCODE
- No side effects
- Behaviour : as if the targeted instruction was a NOP

Corrupt data *[Moro et al. 2013]*

- On LDR instruction
- Random change of the loaded data

Skip the fetch of instructions *[Rivière et al. 2015]*

- Skip the fetch of new instructions
- Re-execute the previously fetched instructions

Fault attacks by Electromagnetic Injection

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Pros :

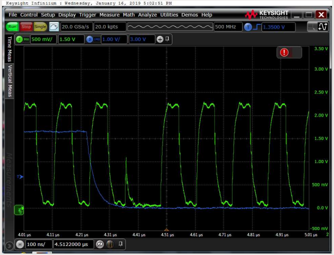
- Non-invasive ✓
- Reproducible ✓

Cons :

- Many parameters to tune ✗
- Low success rate (30%) ✗
- Expensive hardware apparatus ✗
- Limited number of fault ✗

EMI effects on clock signal

Faulted clock signal.

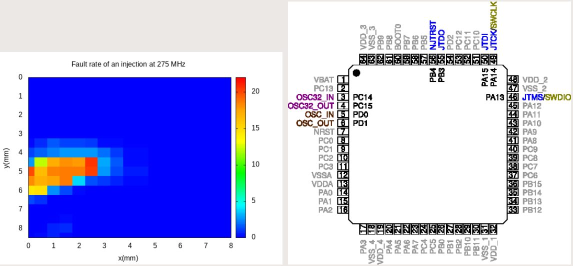


- What is the cause of that unusual behaviour ?
- What if we take control of the clock signal and recreate this glitch whenever we want ?

Plan

1. Electromagnetic Injection (EMI)
2. Clock behaviour in presence of EMI
3. TRAITOR

EMI efficiency vs probe location



(a) Fault rate (%) mapping (b) PIN in/out mapping

FIGURE 1 – Comparison of fault injection mapping with STM32F100RB-LQFP64 PIN map.

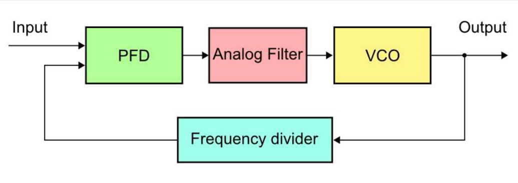
- Strong influence of EMI on clock signal
- Sensitive location = analog feeding pins (including PLL)
- Crystal clock only → fault rate close to 0%

Injection parameter

- 4 sinus periods
- Frequency : 275 MHz
- Power : 175 W
- Delay : 188.5 ns

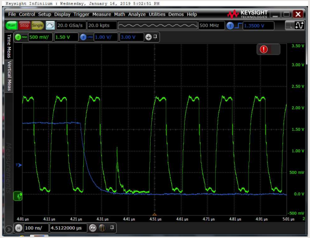
Clock generation by Phase-Locked Loop (PLL)

Clock signal generated by PLL

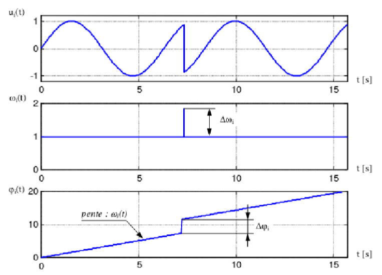


- Input reference = Crystal (8 MHz on for STM32F100RB)
- VCO output wired to clock tree
- Phase-frequence detector → phase comparison VCO vs Crystal
- Phase difference → voltage correction on VCO
- Advantage =
  - Frequency higher than with crystal only
  - Frequency chosen by user

Hypothesis on mechanism



- Global injection inefficient
- Shape of the glitch $\simeq$ shape of VCO output when phase jump
- Hypothesis :
  - disruption on one of the comparator input
  - detection of phase-jump
  - voltage correction on VCO
  - glitch on VCO ouput



Theoretical VCO signal due to phase jump.

Future works

- Confirm the hypothesis by simulation
- Determine the relation between glitch amplitude and phase-difference
- Deduce the shape of the radiated wave for a more efficient EMI

Plan

Reproducing EMI effects in a cheaper way

TRAITOR

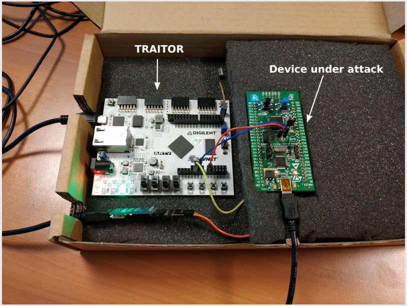
Pros

- Cheap (∼ 100€)✓
- A lot of glitches in a single execution✓
- High success rate (≃ 99%) ✓
- Easily transportable ✓

Cons :

- Access to the crystal required ✗

TRAITOR = FPGA Artix-7
Target = **STM32F100RB**

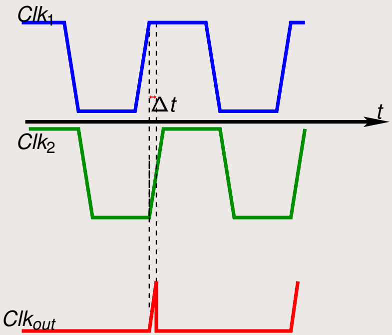


Can completely edit the targeted program during its execution

TRAITOR signal generation

Methods of generation

- Generation of 2 signals slightly unphased
- Glitch : $Clk_{out} = (Clk_1 \oplus Clk_2).Clk_1$
- Pameterization of delays by user
- Switch output to the glitch according to these delays



DEMO : Hacking an almost secure PIN implementation

```
if (check_result(result)){
    // State 0
    Green _light_on( ) ;
    Blue_light_off( ) ;
    if (check_result(result)){
        // State 1
        Green_light_on( ) ;}
        else{
       // State 2
        Blue_light_on( ) ;}
    }
else{
    // State 3
    Blue_light_on( ) ;
    Green_light_off( ) ;
    if (check_result(result)){
        // State 4
        Green_light_on( ) ;}
        else{
        // State 5
        Blue_light_on( ) ;}
}
```

Target = **STM32F100RB**

Fault on Double PIN verification

By default : wrong code PIN is sent to the device ⇒ Blue

- STATE 1 : Green ⇒ Right PIN or Intrusion undetected
- STATE 2 : Blue + Green ⇒ Intrusion warning
- STATE 4 : Blue + Green ⇒ Intrusion warning
- STATE 5 : Blue ⇒ Wrong PIN

DEMO : Hacking an almost secure PIN implementation

```
if (check_result(result)){
    // State 0
    Green _light_on( ) ;
    Blue_light_off( ) ;
    if (check_result(result)){
        // State 1
        Green_light_on( ) ;}
        else{
       // State 2
        Blue_light_on( ) ;}
    }
```

```
800057c:   f000 f91e   bl      80007bc <check_result>
8000580:   4603        mov     r3, r0
8000582:   2b00        cmp     r3, #0
8000584:   d027        beq.n   80005d6 <main+0x352>
8000586:   2201        movs    r2, #1
8000588:   f44f 7100   mov.w   r1, #512          ; 0x200
800058c:   4879        ldr     r0, [pc, #484]    ; (8000774 <main+0x4f0>)
800058e:   f002 fb54   bl      8002c3a <HAL_GPIO_WritePin>
8000594:   f44f 7180   mov.w   r1, #256          ; 0x100
8000598:   4876        ldr     r0, [pc, #472]    ; (8000774 <main+0x4f0>)
800059a:   f002 fb4e   bl      8002c3a <HAL_GPIO_WritePin> ;
800059e:   4b76        ldr     r3, [pc, #472]    ; (8000778 <main+0x4f4>)
80005a0:   681b        ldr     r3, [r3, #0]
80005a2:   4618        mov     r0, r3
80005a4:   f000 f90a   bl      80007bc <check_result>
80005a8:   4603        mov     r3, r0
80005aa:   2b00        cmp     r3, #0
80005ac:   d009        beq.n   80005c2 <main+0x33e>
80005ae:   4b73        ldr     r3, [pc, #460]    ; (800077c <main+0x4f8>)
80005b0:   2201        movs    r2, #1
80005b2:   601a        str     r2, [r3, #0]
80005b4:   2201        movs    r2, #1
80005b6:   f44f 7100   mov.w   r1, #512          ; 0x200
80005ba:   486e        ldr     r0, [pc, #440]    ; (8000774 <main+0x4f0>)
80005bc:   f002 fb3d   bl      8002c3a <HAL_GPIO_WritePin>
80005c0:   e033        b.n     800062a <main+0x3a6>
80005c2:   4b6e        ldr     r3, [pc, #440]    ; (800077c <main+0x4f8>)
80005c4:   2202        movs    r2, #2
80005c6:   601a        str     r2, [r3, #0]
80005c8:   2201        movs    r2, #1
80005ca:   f44f 7180   mov.w   r1, #256          ; 0x100
80005ce:   4869        ldr     r0, [pc, #420]    ; (8000774 <main+0x4f0>)
80005d0:   f002 fb33   bl      8002c3a <HAL_GPIO_WritePin>
80005d4:   e029        b.n     800062a <main+0x3a6>
```

DEMO : Hacking an almost secure PIN implementation

```
800057c:   f000 f91e   bl      80007bc <check_result>
8000580:   4603        mov     r3, r0
8000582:   2b00        cmp     r3, #0
8000584:   d027        beq.n   80005d6 <main+0x352>
8000586:   2201        movs    r2, #1
```

2 possibilities to bypass the tests

- CMP not executed (in the hypothesis the ASPR register is by default in the right state)
- Beq not executed → branch “PIN ok”

Fault model

- Skip instruction fetch and re-execute the instruction(s) previously fetched
- Cortex-M3 = instruction fetched 2 by 2
- !!! Depending in instructions around, fault is not that easy !!!

TRAITOR capabilities

Instruction fault

- Execute twice : mov, ldr, add, push, pop
- Skip fetch of str, mov, ldr, add, push, pop, bl, cmp, bx
- No fetch of some instructions induces most of the time (except str) to re-execute the already fetched instructions
- If wide instruction (32 bits), 1 instruction “nop”.

Application

- Bypass counters by incrementing artificially
- Bypass function (particularly security functions) to avoid countermeasures
- Activation of dead code
- Activation of back-doors
- Rewriting completely the code at run-time combining the previous items

Fun Facts

Glitch voltage influence

- Fault on MOV, LDR, ADD, STR, BL $\simeq$ [630 mV ; 950 mV]
- Depending on the code, for a same clock edge, different voltage induce differents effects

Exotic behaviour 01

```
08000992 <asm_testbranch2>:
 800099e:   6860        ldr    r0, [r4, #4]
 80009a0:   68e1        ldr    r1, [r4, #12]
 80009a2:   69e2        ldr    r2, [r4, #28]
 80009a4:   6aa3        ldr    r3, [r4, #40]   ; 0x28
 80009a6:   f000 f824   bl     80009f2 <asm_br2>
 80009aa:   2500        movs   r5, #0

080009f2 <asm_br2>:
 80009f2:   3007        adds   r0, #7
 80009f4:   3103        adds   r1, #3
 80009f6:   320b        adds   r2, #11
 80009f8:   3305        adds   r3, #5
 80009fa:   4770        bx     lr
```

- Fault just after fetch BL [630 mV ; 1,3 V]
- LR data copied in the destination register of the fourth instruction before branch
- When replacing LDR by MOV Rd, Rm, LR copied in Rm

Exotic behaviour 02

```
08000a14 <asm_testwide>:
 8000a14:   1c04    adds   r4, r0, #0
 8000a16:   46c0    nop
 8000a18:   2000    movs   r0, #0
 8000a1a:   2100    movs   r1, #0
 8000a1c:   2200    movs   r2, #0
 8000a1e:   2300    movs   r3, #0
 8000a20:   6860    ldr    r0, [r4, #4]
 8000a22:   68e1    ldr    r1, [r4, #12]
```

- NOP of *LDR R0,* and *LDR R1,* glitch = [550 mV ; 670 mV] and [770 mV ;870 mV]
- **Get out of the function** after the *MOV R3, #0*, glitch = [670 mV ; 770 mV]
- Strange behaviour independent of the instructions after the branch

Conclusions - Perspectives

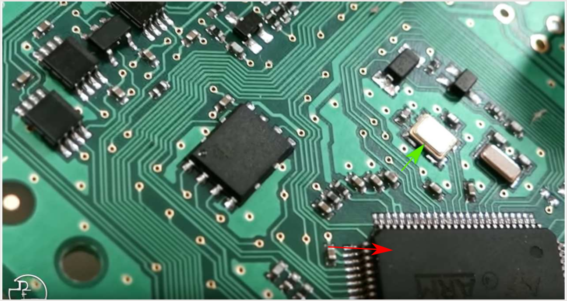
Conclusions on TRAITOR

- Light and transportable platform, easy to use
- Take control of clock signal and inject fault
- Multi-fault $\rightarrow$ can edit a program at run-time and deeply change its goal

Perspectives

- Continue to experiment faults on instruction set
- Applied TRAITOR to other target (TI chip for example)
- Applied multi-fault on real program $\rightarrow$ application case

Thank you !



Board of an everyday object with STM32F2 and its Crystal

Questions ?