Implementing Practical Electrical Glitching Attacks

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About Me

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- Computer Security Consultant at NCC group
- Interest in hardware attacks and hardware security

What are glitching attacks

Glitching Attack

- A glitching attack is an intentional fault introduced to undermine device security
- Some of the things the faults can cause
  - Instruction skipping
  - Malformed data reads/write backs
  - Instruction decoding errors

What are glitching attacks

Noninvasive

- Involves minimal damaging to IC packaging
- Can be done on the cheap
- Relatively simple to implement

Invasive/Semi-Invasive

- Required to decapsulate/modify IC packaging
- Needs fairly expensive equipment
- Potentially a larger amount of time required

What are glitching attacks

Noninvasive types

- Electrical
  - Clock
  - Power
- Thermal
- Radiation

What are glitching attacks

Clock

- Introduce unplanned clock edge(s) to device
- Different glitch signals can be used
  - 3 Phase Xor (See “Gliching for n00bs” by Exide)
  - Direct Xor Duration
  - Increased clock speed

What are glitching attacks

Power

- Pull to ground (brownout)
  - More likely to cause certain instructions to fail
  - More predictable
  - Causes prorogation delays in IC
- Increase voltage (spiking)
  - Easy to implement
  - Also easy to damage target
  - Likely adds more floating signals

Where can we use glitching?

Targets

- Game consoles
- Copy protected IC
- Door locks/Safes
- Set top boxes
- Mobile hotspots

Code

- Authentication checks
- Bounds/sanity checks
- Memory read/writes

Xbox 360 Reset Glitch Hack

- Original exploit and write up by GliGli
- Attack similar to clock glitching attack
- Takes advantage of exposed IC pin interface
- Generally a non patchable exploit
- Only describing exploit on original xbox 360

Xbox 360 Reset Glitch Hack

Xbox 360 Bootloader Security

- Works by chain of bootloaders starting with ROM (1BL) then subsequently loading hypervisor/base kernel, the kernel and then the dash
- Nand code is RSA signed
- Xbox 360 emits out diagnostic signals during this process

Xbox 360 Reset Glitch Hack

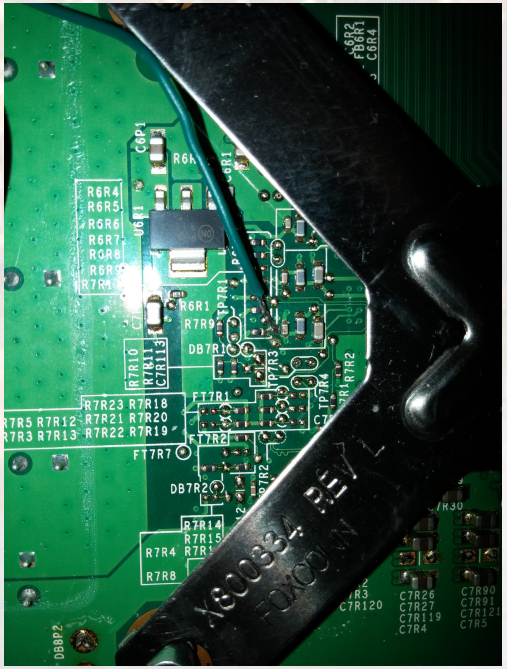
Vulnerable Pin Interfaces

- CPU_PLL_BYPASS
- RESET behavior which skips instruction execution
- Diagnostic POST bus

Xbox 360 Reset Glitch Hack

CPU_PLL_BYPASS

- CPU_PLL_BYPASS slows processor to 520 khz
- Allows for easy timing



Xbox 360 Reset Glitch Hack

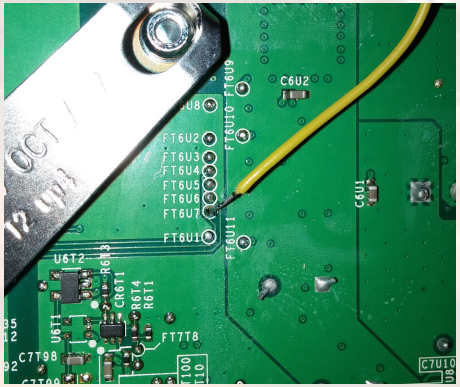
RESET

- CPU Reset is a common feature on most ICs which typically resets execution state
- Processor instead effectively skips instructions when RESET is asserted

Xbox 360 Reset Glitch Hack

POST bus

- POST bus is an 8-bit diagnostic bus
- Emits signals for important steps of the booting process
- Sends 0x36 when decrypting CD and 0x39 when comparing the hash



Xbox 360 Reset Glitch Hack

What the exploit targets

- Target's signature check
- Use POST bus signals to know when to do so

About the payload

- Payload is set up in a way that resets the xbox when it fails
- Indicator about the nature of glitching

Xbox 360 Reset Glitch Hack

Exploit

1. Upload payload to NAND
2. Monitor for POST 0x36 (decrypting the base kernel)
3. Assert CPU_PLL_BYPASS
4. Monitor for POST 0x39
5. Start internal counter to end at ~62% of the POST 0x39 length
6. Assert RESET for 100 ns at end of counter duration
7. Resume normal execution

Xbox 360 Reset Glitch Hack

Vendor Response

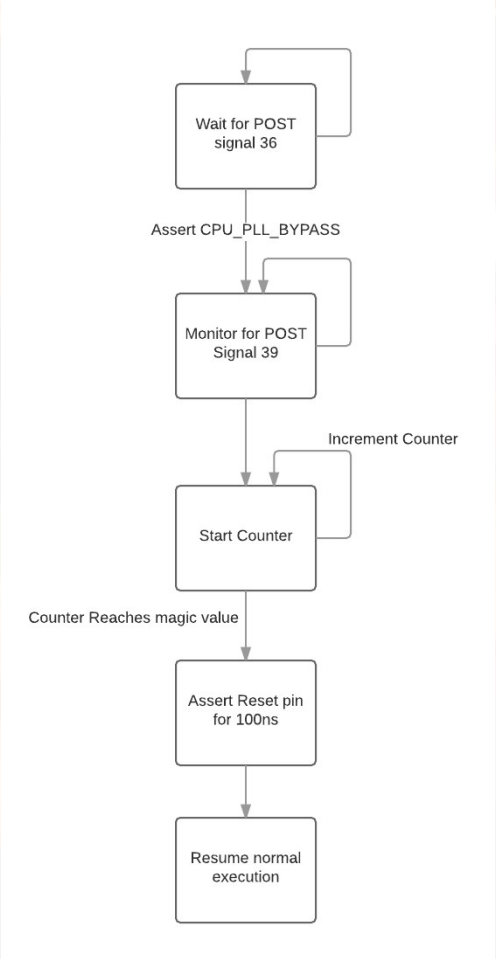
- Dash version 7371 destroyed JTAG fuses
- Additional check added to loading of base kernel
- Began banning users from Xbox Live

Xbox 360 Reset Glitch Hack

Reset Glitch 2.0

- Exploit said to work on all original xbox 360s
- Makes use of i2C bus on xbox 360 to slow down clock
- Made use of NAND “DemoN” to avoid getting Xbox Live bans

Xbox 360 Reset Glitch Hack



Attack Methodology

General Methodology

- Assess target device for target code
- Review datasheet of target IC
- Test target threshold manually
- Find points to attack on target device
- Search for signals on target device
- Prepare target for glitching
- Setup FPGA for brute forcing of glitching parameters
- Begin attack

Attack Methodology

Choosing target code

- Search for checks which use instructions longer than one cycle
- Instructions with write back
- Security checks near computationally intense code
- Easy/Quick to reset state upon failure
- Code near boot sequence or near kernel operations

Attack Methodology

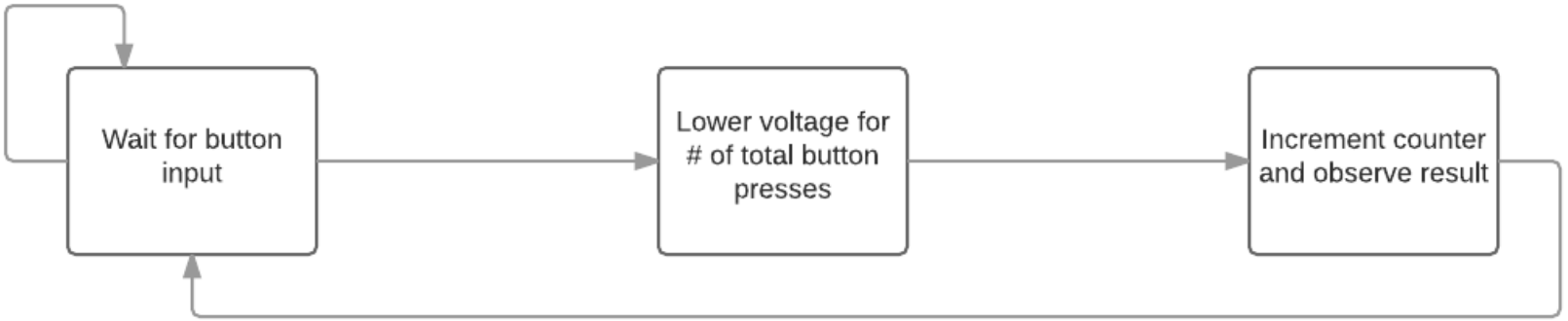
Reviewing Datasheets

- Operational ranges
- Brownout detection
- Security features (if any)
- Rated clock speeds
- Interesting pin interfaces

Attack Methodology

Testing target threshold manually

- Useful if the target device has a development board
- Test brownout threshold
- Duty cycle testing of device
- View delay ranges of example instructions in practice



Attack Methodology

Findings points to attack on a device

- External crystals
- Decoupling capacitors
- Voltage regulators
- Voltage dividers
- Power supply

Attack Methodology

Signals

- Signals are information emitted from the device which allows us to narrow the values we have to guess
- They vary greatly in terms of value due to noise introduced during execution
- The parameter we are guessing here is the delay range maximum
- Signals can be used to start the delay state or to close in closer to the signal which does that

Attack Methodology

What a signal can be

- GPIO toggling
- Status LEDs
- Serial Messages
- Device specific diagnostic buses
- Power analysis
- Calculation of instruction timings from input
- Raw timing window

Attack Methodology

Calculating timing from disassembly

- Signal delays can sometimes be calculated to a tight range
- This requires the target code to be writing out somewhere within close proximity
- During the experiments the following equation had a generally good result

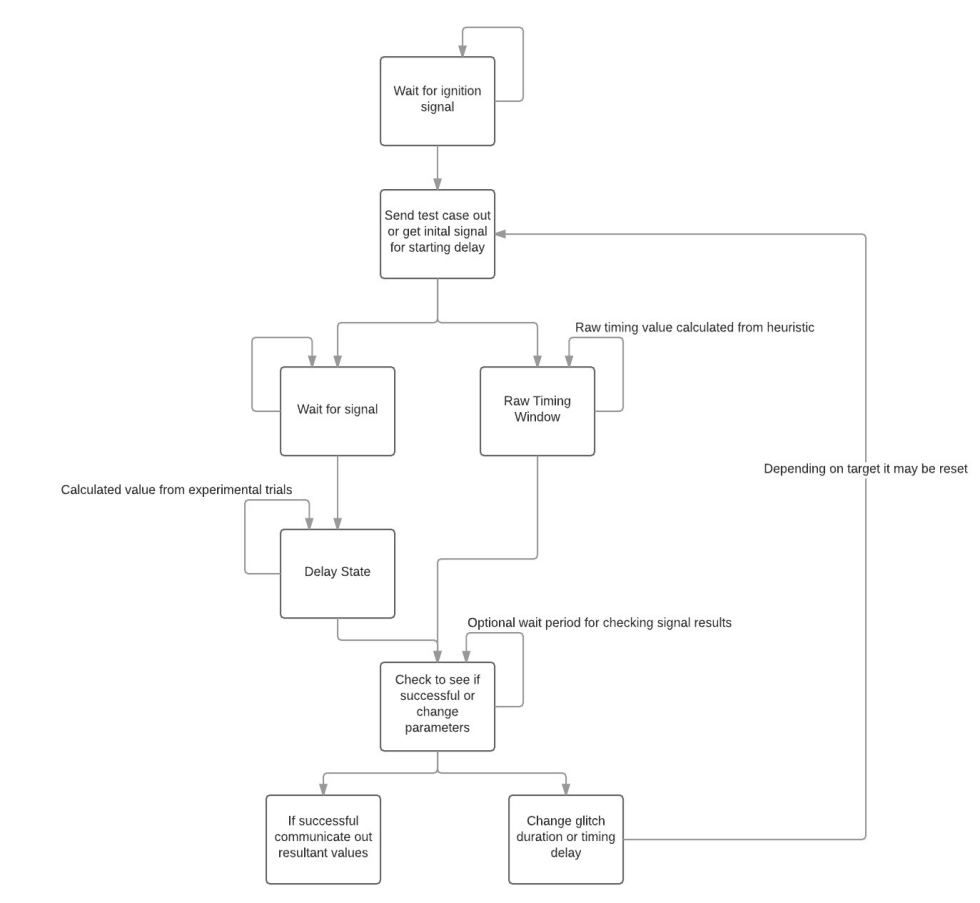
$$[\frac{i_{instCount} T_{target}}{T_{Glitch}} - 3P_{size}, \frac{i_{cycleCount} T_{target}}{T_{Glitch}} + 3P_{size}]$$

Attack Methodology

Preparing the device

- What is desoldered or not is dependent on the type of glitch used
- Clock glitching involves removal of the device crystal and its 2 nearby decoupling capacitors
- Voltage spiking involves finding a VCC decoupling capacitor and soldering to the high side of the capacitor
- Voltage brownout attacks work best by removing all of the power decoupling capacitors and then either cutting the line on the PCB or finding a nearby voltage regulator

Attack Methodology



Attack Methodology

Glitching parameters

- Glitch duration
  - Typically maxed out by datasheet values or experimental values
  - Suggest for clock glitching signal to at least cover one full cycle
- Delay length
  - Determined by signals or by calculations from disassembly
  - Parameter with the widest range
- Glitch Attempts
  - Glitching is not always accurate, and can often require more than one try to work
  - Targeting a state which can be quickly recovered greatly accelerates process

Attack Methodology

Possible FPGA Glitching Components

- Glitching device
  - Defined as device which emits out the supplied glitch signal
  - Should not be changed very often
- Test case device
  - Optional device which emits out test case to the target device
  - Emits signal back to the glitching device of when the test case is done
- Sampling device
  - Device which signals back to the glitching device whether the glitch was successful
  - Condition for tests of whether attack is successful should have highest precedence

Tools used

- Used DE0 Nano FPGA device
- When choosing a FPGA dev board for attacks consider its speed
- Attacks implemented used multiple GPIO pins
- Also used switching transistors for trying attacks on 5V logic devices
- Consider output voltage and maximum clock speed when choosing an FPGA

ATMega328p

Attacks Used

- Clock Glitching
  - Got fairly consistent results from it
- VCC Brownout

Code Targeted

- Simple code to glitch out of extremely long loop
- Used 2 devices which had different delay values in them

ATMega328p

- Was used as a starting example
- Both glitching attacks were direct input to the device
- Used standard breadboard setup
- Reset target device during non response
- Gained fairly consistent results on both attacks for values found
- Performed attacks where FPGA directly supplied what was being glitched

ATMega328p

Signal used

- Used timing of target toggling LED on and off

Threshold testing

- To test brownout limit, we employ the simple state machine from before slowly incrementing the power off until the example code turns the LED off
- During duty cycle testing I found that it runs off of very small duty cycles of ~8%

ATMega328p

Threshold Testing results

- Datasheet claims that the timeout period was 2 us
- The limit was found to be 200ns in practice

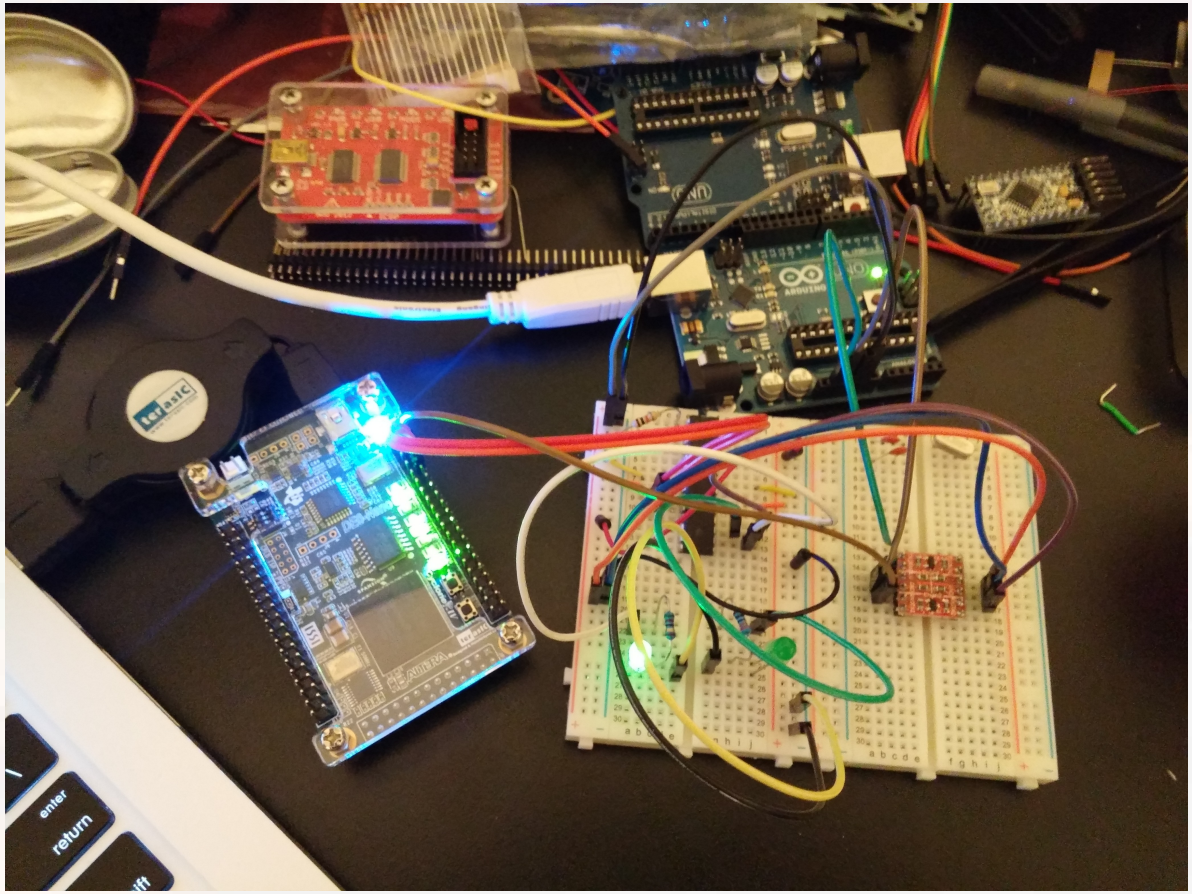
ATMega328p

Instruction Counting in practice

- When a direct count according to the disassembly was tried, the attack failed
- Instead when a range was used the attack succeeded
- The actual value for the delays were smaller than expected
- Used signal to help locate when to start counter
- P_size -> pipeline size, T_* -> period
- Rough heuristic equation used to brute force delay value from ideal signal

$$\left[\frac{i_{instCount}\,T_{target}}{T_{Glitch}} - 3P_{size},\ \frac{i_{cycleCount}\,T_{target}}{T_{Glitch}} + 3P_{size}\right]$$

ATMega328p Clock Setup



ATMega328p

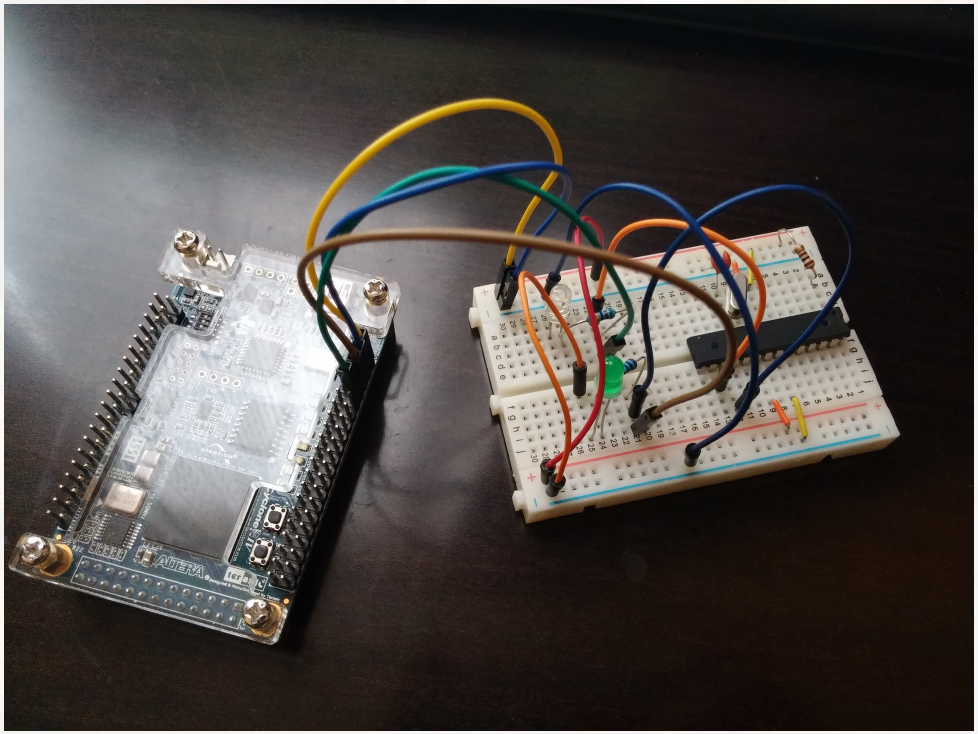
Clock Glitching

- Used duration of 60-80 ns for glitch pulse
- Directly xored against 16MHz clock supplied
- Found fairly consistent timing delays
- Value found was smaller than expected

ATMega328p Voltage Setup

About

- The ATMega328p can run off of both 3.3v and 5v making this easier



ATMega328p

Voltage Glitching

- Performed Brownout glitching
- Had fairly similar timings
- Durations varied for successful attempts
- Generally took more tries to work than the clock glitching setup
- If possible directly power target device

ATMega328p

FPGA Parts

- Glitch device
  - Used direct xor, and 3 phase xor successfully
  - Maxed out brownout timing to be the maximum tested threshold
- Test Case
  - Waited for LED to turn on then off again
  - Helped gain a smaller window to timing
- Sampler
  - Direct connection to LED which turns on after a successful branch skip
  - Checked at the top level of the glitch device code

ATMega328p

Problems Encountered

- FPGA IDE issues
- Logic translation between ATMega328p and FPGA
- Analog problems
- Extra delay introduced from transistor switch

LPC1343

What it is

- ARM development board from programmable logic training class
- Communicates out over serial asking for password
- Meant to be a timing attack example
- Completely blackbox example

LPC1343

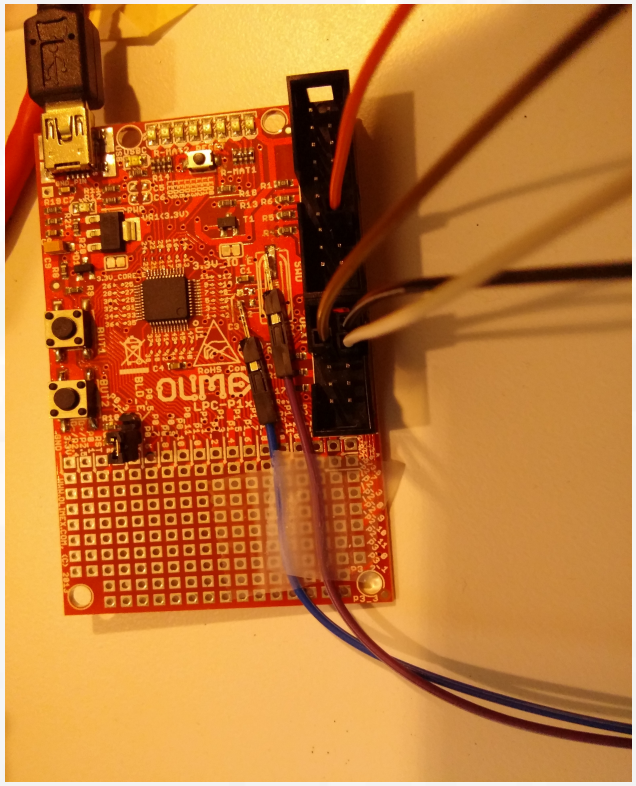
Signal used

- Used response from serial to determine the timing window
- Also monitored for “I” in message to determine if the response was successful or not
- Required FPGA to send input to device before glitching
- Signal had large ranges in practice
- Needed a post glitch wait phase to allow parsing of serial input to determine if a good value has been found

LPC1343

Preparing the board

- Removed crystal on board with a bit of heat and mechanical force
- Also removed decoupling capacitors



ATMega328p

FPGA Parts

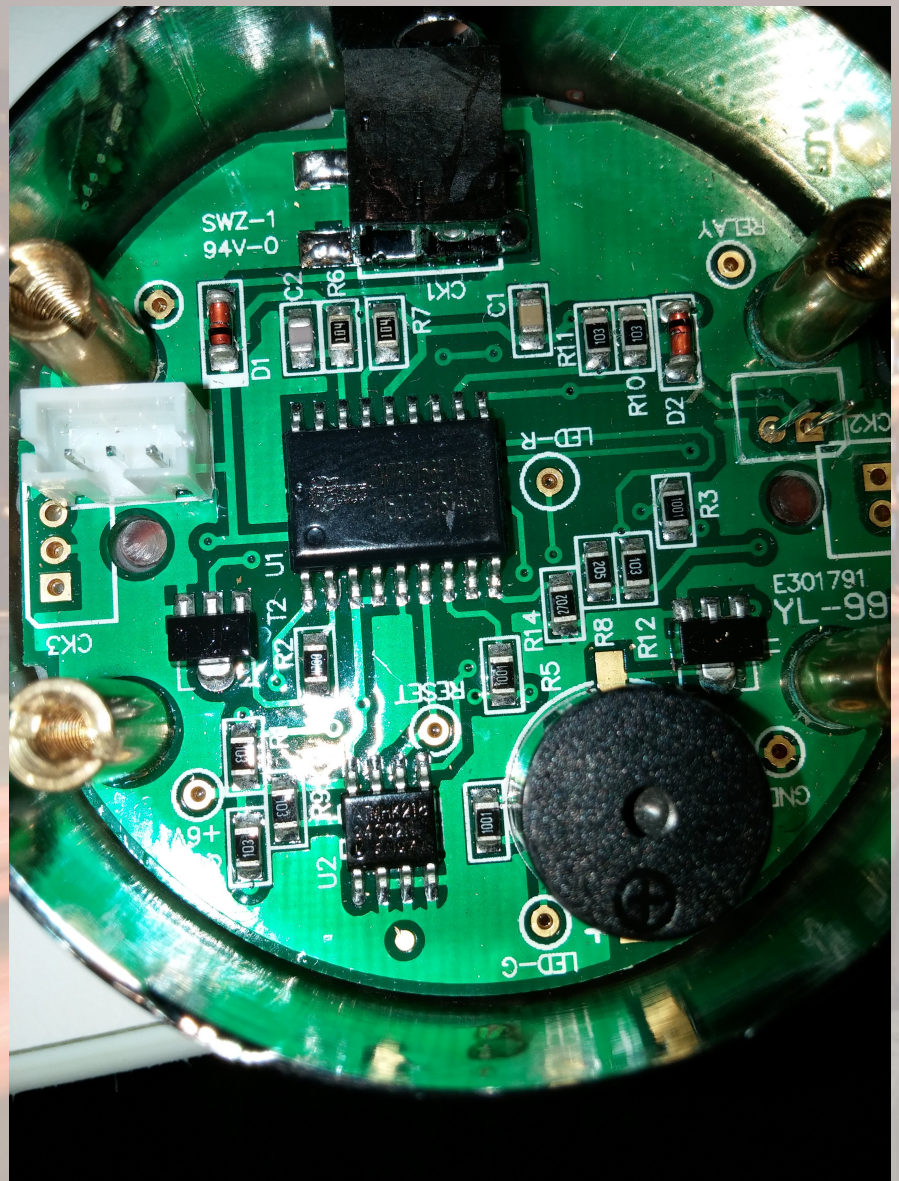
- Glitch device
  - Only attempted clock glitching
  - Virtually the same verilog code to the previous example
- Test Case
  - Sent out 17 “A”s to the target device over serial
- Sampler
  - Monitor to check for incorrect password message
  - If the message does not match send back the parameters used over serial

LPC1343

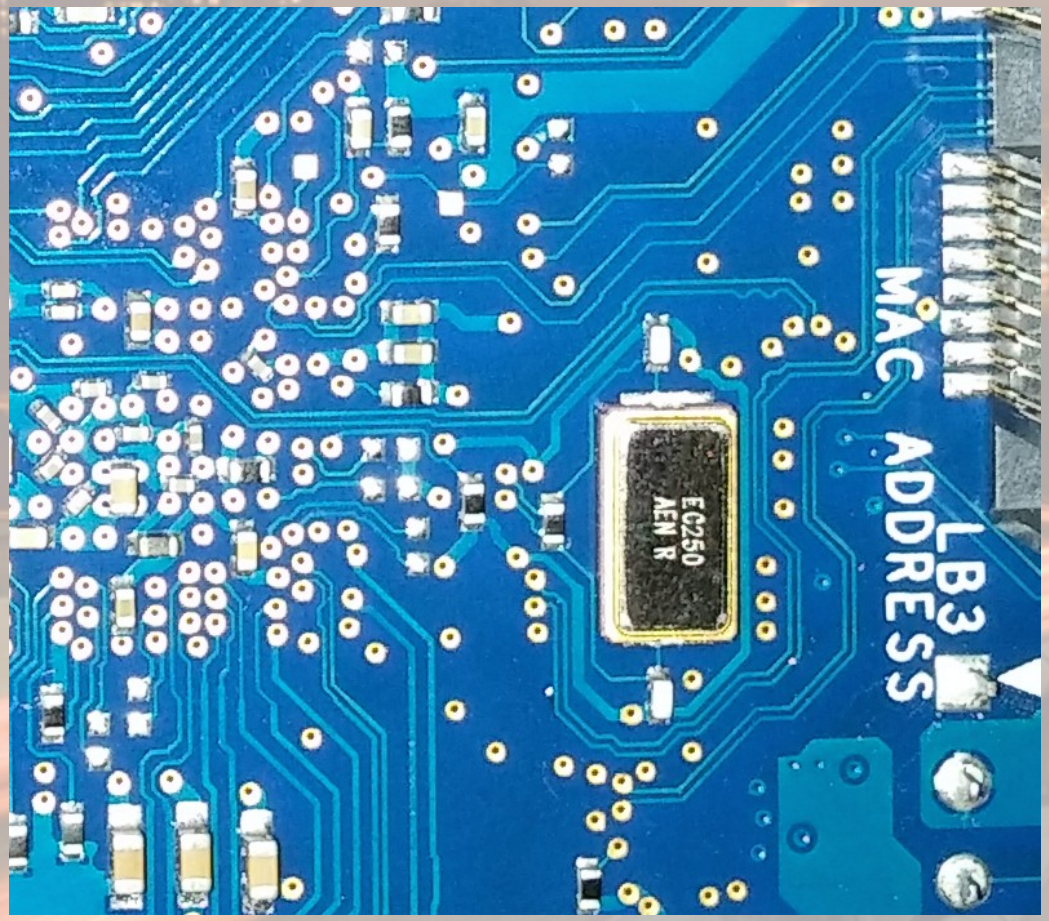
Conclusions

- Serial interface messages are alright to use as a signal
- Finding the correct glitching parameters black box is fairly difficult
- Glitching parameters vary depending on the situation and device architecture

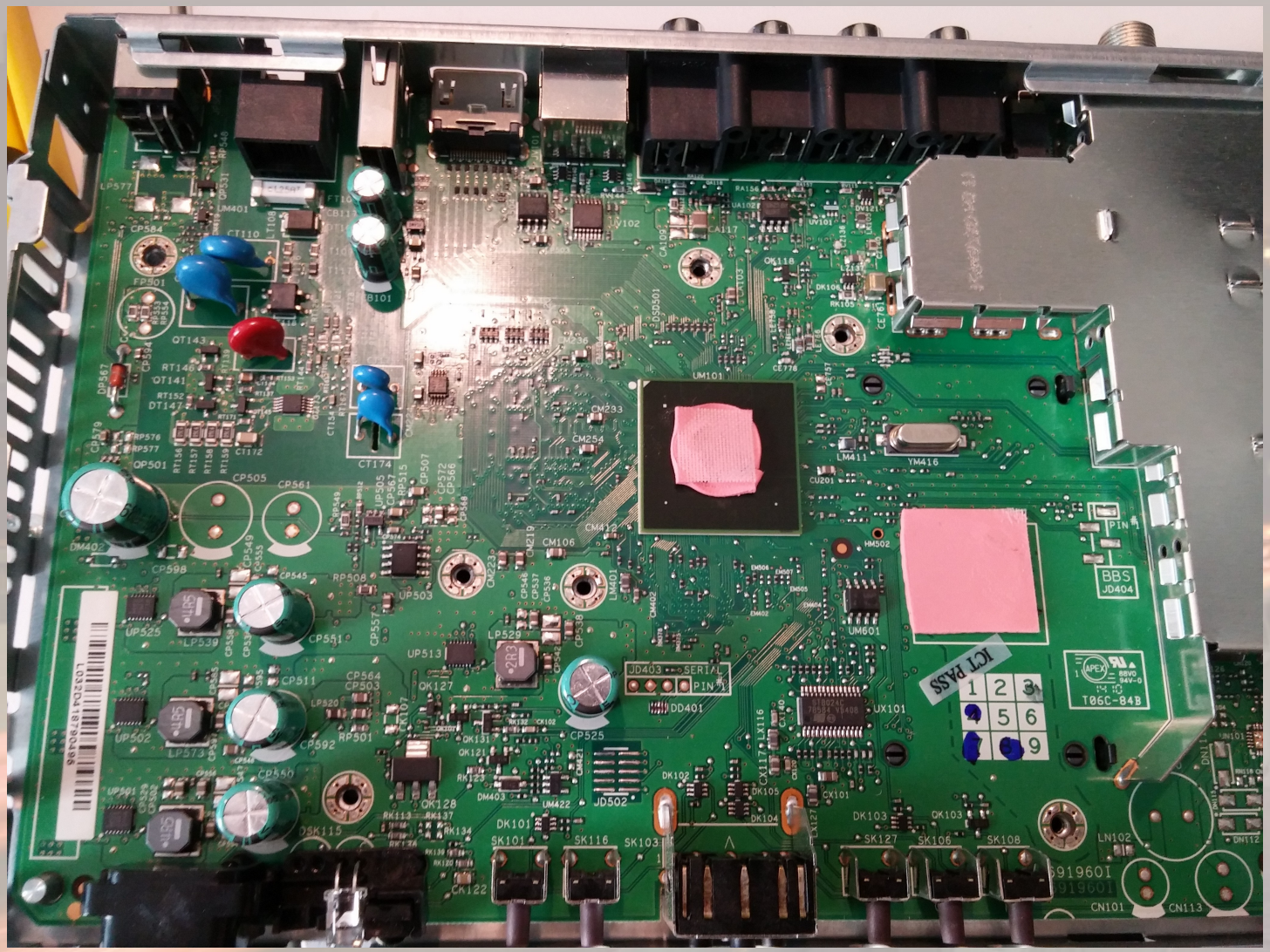
Example Enumeration - Door Lock



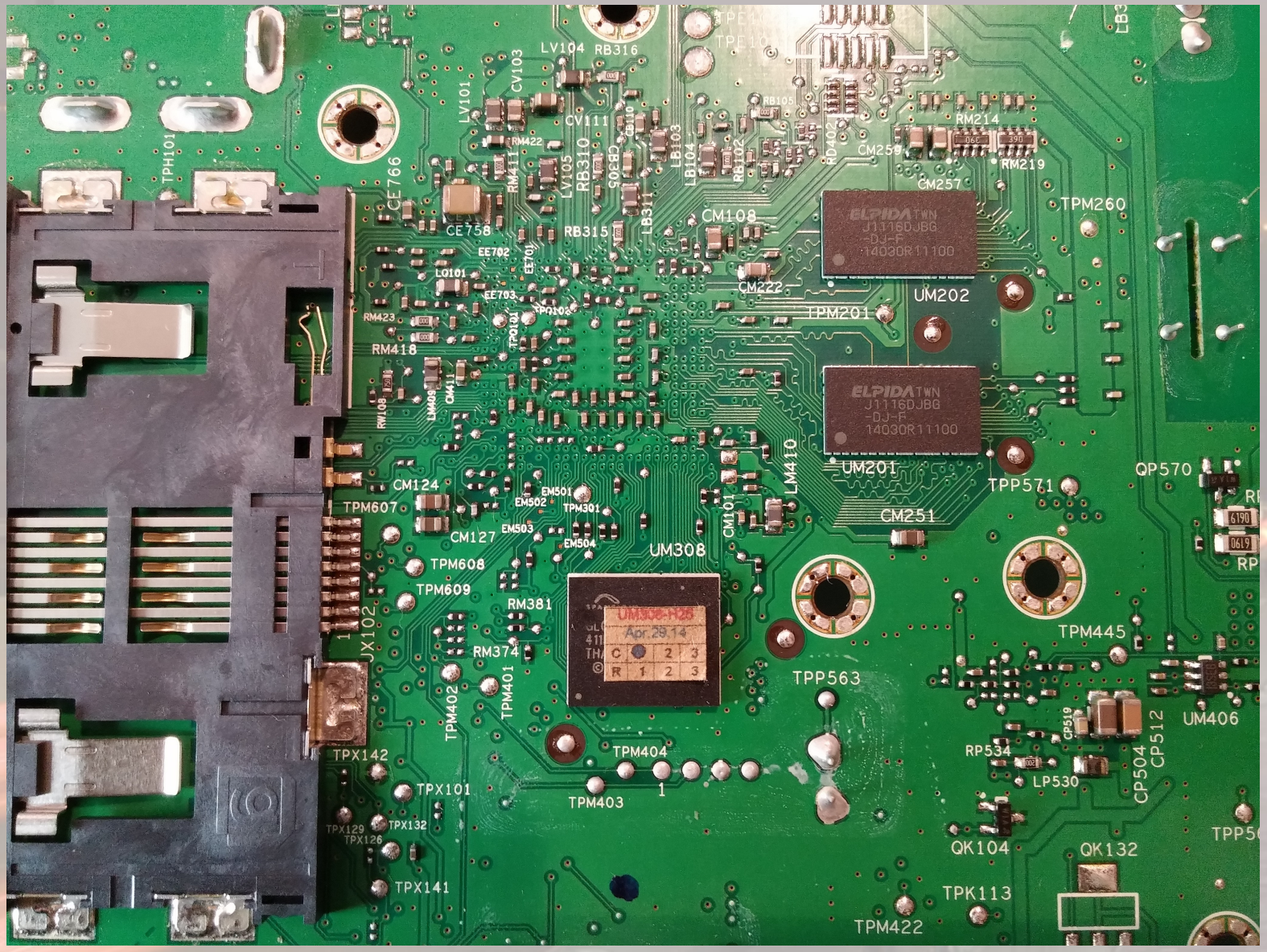
Example Enumeration - Intel Galileo



Example Enumeration - Set top box



Example Enumeration - Set top box



Experiments for the future

- Clock gltiching on a device with a frequency multiplier
- Attacking devices which claim to have mitigations
- Combining multiple types of glitching attacks
- Attacking memory devices
- Implementing an attack on code running on top of an operating system

Defenses Against Glitching

- Glitch detectors
- High quality brownout detection
- Lockstep cores performing checks on one another
- Asynchronous internal clock with dummy cycles
- Internal Oscillators
- Halt on invalid instruction execution
- Lock down unnecessary diagnostic signals

Defenses Against Glitching

- Search for ICs which use mitigations against glitching
- Perform assessments against the IC before using it in production
- Writing code defensive in the case of a glitching attack would only buy time

Conclusions

- Glitching attacks are cheap, though can vary in implementation.
- When performing a glitching attack, multiple tries are often required.
- Try before you buy if you are an embedded system vendor.

References / Suggested Reading

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- Glitching and Side Channel Analysis for all , Colin O'Flynn RECON 2015
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Locations

North America
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Austin
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Seattle
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Manchester - Head Office
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Leatherhead
Leeds
London
Luxembourg
Malmö
Milton Keynes
Munich
Vilnius
Wetherby
Zurich

Australia
Sydney

Agenda

- What are electrical glitching attacks
- Where are they applicable
- Reset Glitch Hack on the Xbox 360
- Methodology for performing an attack
- Tools used
- Atmega328p
- LPC1343
- Example Enumeration
- Glitching experiments for the future
- Defenses against glitching