Closer to metal: Reverse engineering the Broadcom NetExtreme's firmware

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Purpose of this presentation

Hardware trust?

- Hardware manufacturers are reluctant to disclose their specifications
- You do not really know what firmwares do behind your back
- Consequently you cannot really trust them...
- So here comes the need for *reverse engineering*

Previous works

- **A SSH server in your NIC**, Arrigo Triulzi, PacSec 2008
- **Can you still trust your network card?**, Y-A Perez, L. Duflot, CanSecWest 2010

Purpose of this presentation

What is this presentation about?

- Reverse engineering of the Broadcom Ethernet NetExtreme firmware
- Building an instrumentation toolset for the device
- Developing a new firmware from scratch

Why?

- To have a better understanding of the device internals
- To look for vulnerabilities inside the firmware code
- To develop an open-source alternative firmware for the community
- To develop a rootkit firmware embedded in the network card!

Plan

1. Overview of the NIC architecture
2. Instrumenting the network card. . .
3. . . . and developing a new firmware

Where should we begin?

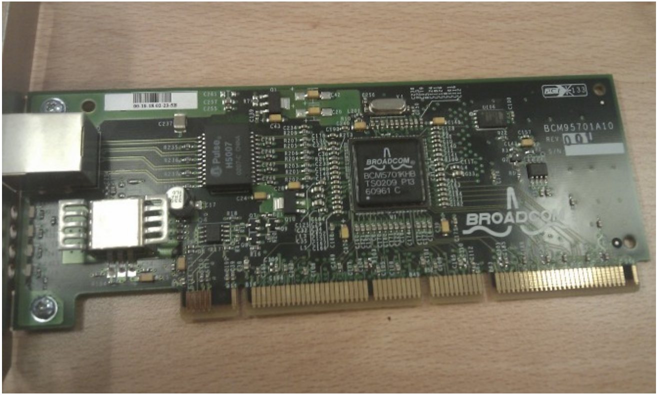
About the target

- Targeted hardware: Broadcom Ethernet NetExtreme NIC
- Standard range of Ethernet cards family from Broadcom
- Massively installed on personal laptops, home computers, enterprises. . .

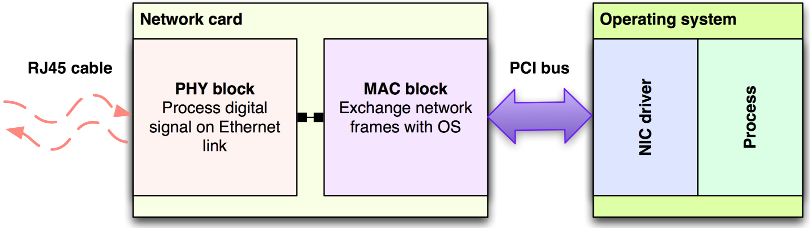
Sources

- Broadcom device specifications (incomplete, sometimes erroneous)
- Linux open-source kernel module (tg3)
- A firmware code is published as a binary blob in the kernel tree
- It is actually not loaded by the Linux driver

The targeted device



NIC overview



Device overview

Core blocks

- The PHY block
  - DSP on the Ethernet link
  - Passes raw data to the MAC block
- The MAC block
  - Processes and queues network frames
  - Passes them to the driver

MAC components

- one or two MIPS CPU
- a non-volatile EEPROM memory
- a volatile SRAM memory
- a set of *registers* to configure the device

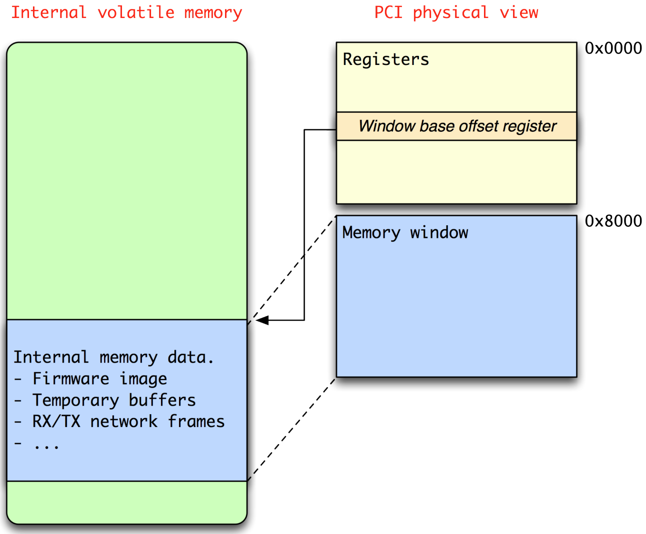
Communicating with the device

PCI interface

- Cards are connected to the **PCI bus**
- Device is accessible using memory-mapped I/O
- Mapped on 16 bits (64 KB)
  - First 32 KB are a direct mapping onto the device registers
  - Last 32 KB constitute a R/W window into the internal volatile memory
  - The base of the window can be set using a register
- EEPROM memory can be accessed in R/W using a dedicated set of registers

We have access to registers, volatile and EEPROM memory through the PCI bus.

Physical PCI view



Different kinds of memory

EEPROM

- Manufacturer's information, MAC address, ...
- Firmware images
- **Non-documented** format

Volatile memory

- Copy of the firmware image executed by the CPU
- Network packet structures, temporary buffers

Registers

- **MANY** registers to configure and control the device
- Some of them are non-documented

Plan

1. Overview of the NIC architecture
2. Instrumenting the network card...
3. ...and developing a new firmware

Instrumenting the device

We want to

- Get easy access to all kinds of memory
- Dump the executing firmware code
- Inject and execute some code
- Test it
- Debug it

At first we have to easily access the device's memory, so we are going to write a little **kernel module**.

Plan

1. Overview of the NIC architecture
2. Instrumenting the network card. . .
   - Accessing the device's internal memory
   - Getting to debug firmware code
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Linux Kernel Module

Basics

- At boot time, the BIOS assigns each device a physical memory range
- The OS maps this range onto a virtual address range
- In MMIO mode, we have to get the device's base virtual address then just access it like any other memory

A kernel proxy between the NIC and userland

- The module provides primitives for reading and writing inside the NIC (registers, volatile, EEPROM)
- It exposes them to userland by creating a virtual char device
- Processes can then use `open`, `read`, `write`, `seek` syscalls

Extracting the firmware code

Firmware dump

- We can dump the executed firmware code from userland
- Based at address `0x10000` in volatile memory (refering to the specs)
- We can directly disassemble MIPS code, obviously it is not encrypted, nor obfuscated

Static analysis

- Static disassembly analysis already made possible
- **We will focus on how to dynamically analyze the executed code**

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Going further

Plan

- Using this kernel proxy, we can easily dump and modify the device's memory from userland
- Now we have to control what is executed on the NIC, the firmware code

Two firmware debuggers

InVitroDbg is a firmware emulator based on a modified Qemu.

InVivoDbg is a real firmware debugger to control code executed on the NIC.

Both use the kernel proxy to interact with the NIC.

InVitroDbg

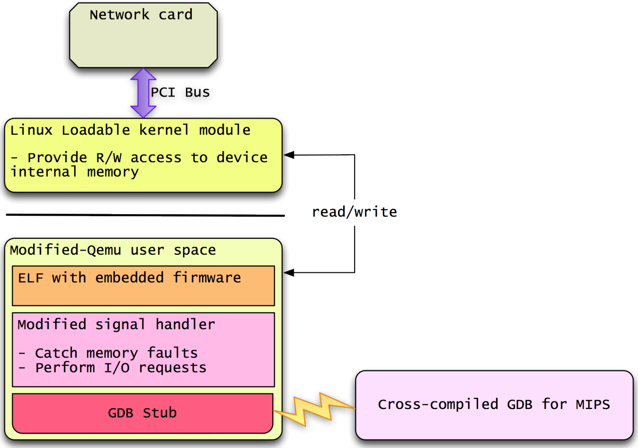
A firmware emulator

- Emulates the NIC MIPS CPU
- Interacts with the physical NIC memory

Mechanism

- Based on a modified Qemu
- Firmware code embedded in a userland ELF executable
- Code segment mapped at the firmware base address
- Catches memory faults and redirects accesses to the real device
- Debugging made possible using the GDB stub of Qemu

Architecture de InVitroDbg



InVivoDbg

Firmware debugger

- Firmware code really executed on the NIC
- Controlling the CPU using dedicated registers

Mechanism

- CPU control with NIC registers: `halt`, `resume`, `hbp`
- CPU registers found in non-documented NIC registers
- Debugger core written in Ruby
- Integrated with the Metasm dissassembly framework
- Real-time IDA-like graphical interface for debugging

Debuggers comparison

InVitro

- Firmware code executed in userland
- No injection in the device memory
- A **lot** of transactions on the PCI bus
- Fake memory view from the PCI bus

InVivo

- IDA-like GUI
- Easily extensible with Ruby scripts
- Few PCI transactions required
- Real memory view from the NIC CPU

Extending InVivoDbg

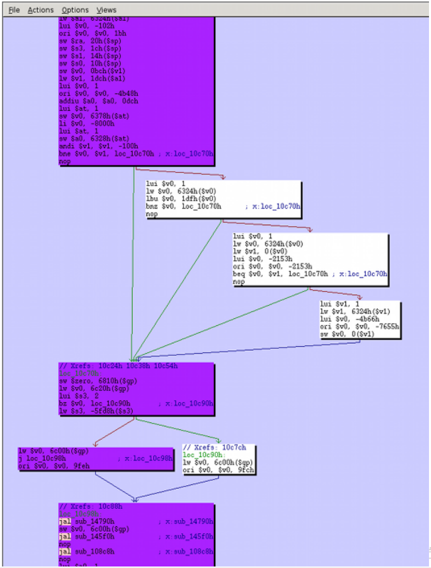
Execution flow tracing

- Reuse the Metasm plugin BinTrace (A. Gazet & Y. Guillot)
- Log every basic block executed
- Save a trace which can be visualized offline
- Support differential analysis of different traces

Interest

- Quickly visualize the default execution path of the code
- Monitor the effect of various stimuli (received packet, driver communication...) on execution

Execution flow trace



Extending InVivoDbg

Memory access tracing

- Step-by-step firmware code
- Log each memory access (`lw`, `sw`, `lh`, `sh`, `lb`, `sb`)
- Save the generated trace
- Replay the trace

Interest

- Does not rely on firmware code analysis
- Extracts the very core behavior of the firmware
- Logs every register access tells us what the firmware is actually doing, e.g. how it configures the device

Memory access trace

```
0x109c8: READ at address 0xc0000400
0x109f0: WRITE 0x00000012 at address 0xc000045c
0x109f8: WRITE 0x00000006 at address 0xc0000468
0x10a00: WRITE 0x00010000 at address 0xc0006800
0x10a08: WRITE 0x00000001 at address 0xc0005ce0
0x10a0c: WRITE 0x00000001 at address 0xc0005cc0
0x10a14: WRITE 0x00000001 at address 0xc0005cb0
```

Plan

Creating a new firmware: what for?

Multiple purposes

- Provides an open-source alternative to proprietary firmware
- Creates a rootkit firmware resident in the NIC

Code testing

- We control the firmware image in volatile memory
- We control the MIPS CPU state
- Thus we can quickly inject and test code in memory
- **How to get our code loaded during the device bootstrap?**

Plan

1. Overview of the NIC architecture
2. Instrumenting the network card. . .
3. . . . and developing a new firmware
   - Reversing the EEPROM format
   - Description of the bootstrap process
   - Building your own firmware

Reversing the EEPROM format

Non-documented format

- EEPROM contains non-volatile data
- Data is r/w accessible using specific device registers
- Format is **not documented** by Broadcom spec. sheets

Contents

- Discovered by firmware code and memory analysis
- It contains
    - A bootstrap header
    - Device metadata (manufacturer's id, device revision...)
    - Device configuration (MAC, voltages, ...)
    - A set of firmware images (bootstrap code, default image, PXE...)

Plan

Description of the bootstrap process

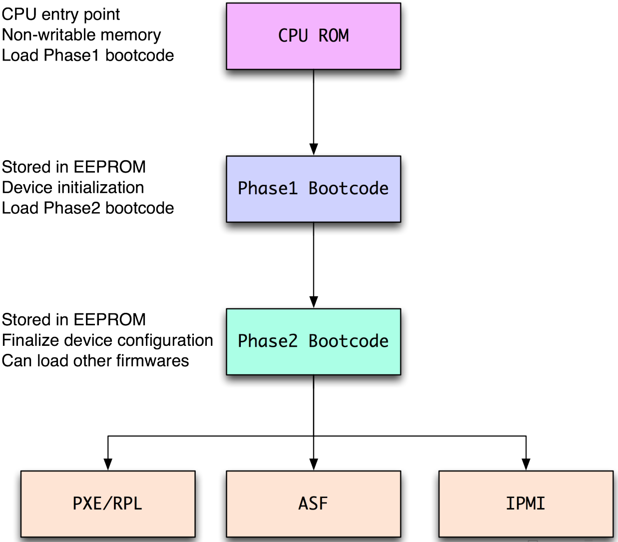
Firmware bootstrap

- How is the firmware loaded from EEPROM to volatile memory ?
- Method: reset the device and stop the CPU as quick as possible!
- Result: CPU executes code at address 0x4000_0000

So?

- This memory zone is **execute-only** (not read/write), probably a ROM
- Hack: An non-documented device register holds the current dword pointed by $pc
- **We can dump the ROM** by modifying $pc and polling this register!

Description of the bootstrap process



Description of the bootstrap process

No trusted bootstrap sequence!

Bootstrap

Every time the source power is plugged-in, or a PCI reset is issued, or the reset register is set:

1. CPU starts on a **boot ROM**
   1. Initializes EEPROM access
   2. Loads bootstrap firmware in memory from EEPROM
2. Execution of the **bootstrap firmware**
   1. Configures the core of the device (power, clocks. . .)
   2. Loads a second-stage firmware from EEPROM
3. Execution of the **second-stage firmware**
   - Is the default firmare executed
   - Configures networking (Ethernet link, MAC, . . .)
   - Can load another firmware if requested

Plan

Developing your own firmware

Building our own firmware

All we need is

- A cross-compiled `binutils` for MIPS
- `ld`-scripting to map the firmware at `0x10000`
- We can start developing our firmware in C
- Inject our firmware in the EEPROM

Memory mapping

- Memory view from the CPU is documented in the specs
- Volatile memory is accessible from address `0`
- Memory greater than `0xC000_0000` maps into device registers

Developing our own firmware

Size requirements

- Code can reside between `0x10000` and `0x1c000`
- 48 KB memory shared by code, stack, and incoming packet buffers

Firmware structure

- Initialize the stack (`$sp = 0x1c000`)
- Configure the device for working (way far beyond this talk)
- Perform custom malicious/fun actions from the NIC!

Examples of customized firmware

Remote firmware debugger

- Remote debugging using the Ethernet link
- Would offer debugging even if the machine is shut down

Rootkit capabilities

- Rootkit (still in development)
- Take over the network
  - Packet interception/forge by the firmware
  - Embedding an IP/UDP stack and a light DHCP client
  - → Stealthy communication (OS never aware)
- Corrupt physical memory
  - Reuse DMA capabilities over PCI to corrupt system RAM
  - Write access OK, read access still unstable
- **The device and the OS driver still have to work properly!**

Conclusion

In a nutshell. . .

- Reverse engineering of a proprietary firmware for security purpose
  - Made possible with a few free open-source tools (Qemu, Ruby, Metasm, binutils, . . .)
  - Real-time firmware debugging!
  - But depends on targeted device (here Broadcom NICs)
- No firmware signature/encryption in Broadcom Ethernet NICs
- One can build and load its own firmware
  - To offer an open-source alternative for the community
  - To build a highly stealthy rootkit embedded in the NIC

Thank you for your attention!

Questions?