Run-time firmware integrity verification: what if you can't trust your network card?

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Embedded devices

- Embedded systems are increasingly prevalent in computers
  - Network cards, hard drive controllers, chipsets, basebands, etc.
  - Some have high processing capabilities ("smart" devices)
  - They act as black-box execution environments
- They constitute a potential threat for the platforms' security
  - They have access to sensitive information
  - They generally lack the protections available on standard processors (e.g., an MMU)
  - They potentially run with high privileges w.r.t the main operating system

Attacks against embedded devices

- Vulnerabilities were found in several embedded software and firmware in the past few years :

Basebands	Weinmann [13]
Network controllers	Duflot and Perez [4], Triulzi [12], Delugré [3]
Keyboard controllers	Chen [2], Gazet [6]
Chipsets	Ortega and Sacco [9]

- Defending a system against such attacks is difficult because firmware are running out of the scope of the operating system.
- Existing IDSes have probably overlooked these attacks
  - they mainly monitor the operating system and applications
  - those attacks are still quite new

Example from our own proof-of-concept attack

- In [4], we demonstrated how it is possible for an attacker to take full control of a computer
  - by exploiting a vulnerability in the network adapter, and
  - adding a back-door in the OS kernel using DMA accesses ;
  - the back-door opens a reverse shell when the kernel processes an ICMP message with a particular type.
- Our proof-of-concept attack was based on a real world vulnerability
  - the vulnerability lied in the `ASF` remote administration function of the network adapter of the target machine.
  - it was unconditionally exploitable when the `ASF` function was activated to any attacker that would be able to send UDP packets to the machine.

Problems & existing solutions

Compromised device?

Consequences

system
- full OS compromise
- rootkit re-injection at startup

Counter-measures

system
- `I/O MMU` (Intel `Vt-d` and AMD `IOMMU`)

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platform
- PCI Express *Access Control Services*

Problems & existing solutions

Compromised device?

Consequences

system	▶ full OS compromise ▶ rootkit re-injection at startup
platform	▶ attacks against other devices on the same buses [11]
network	▶ silent data leak ▶ stepping stone to attack the whole network silently ▶ won't be blocked by firewalls on vulnerable machines

Counter-measures

system	▶ `I/O MMU` (Intel `Vt-d` and AMD `IOMMU`)
platform	▶ PCI Express *Access Control Services*
network	▶ ?

Firmware integrity checks

We need to check the firmware's integrity

- At load time
  - Peripherals' firmware should be measured during a *trusted boot*
  - This can be achieved by means of a TPM
- **At runtime**
  - Our objective is to check that the firmware is running untampered
  - The operating system acts as the verifier of the network card's execution
  - We assume that the operating system is trusted

Existing solutions

Remote firmware attestation [7, 8] ?

- Based on a challenge-response protocol
  - The target computes a checksum over its entire memory
  - The verifier checks the correctness of the returned checksum

Existing solutions

Remote firmware attestation [7, 8] ?

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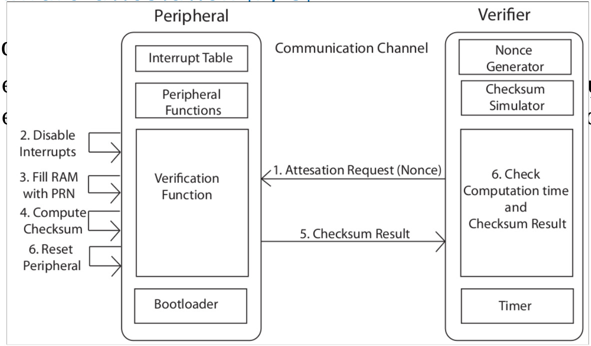

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  - Severe constraints imposed by the checksum function execution
  - Is it really suitable for a network card?

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Software symbiotes ?

- might be an interesting solution, requires further investigations
- seems quite intrusive

What is a network card?

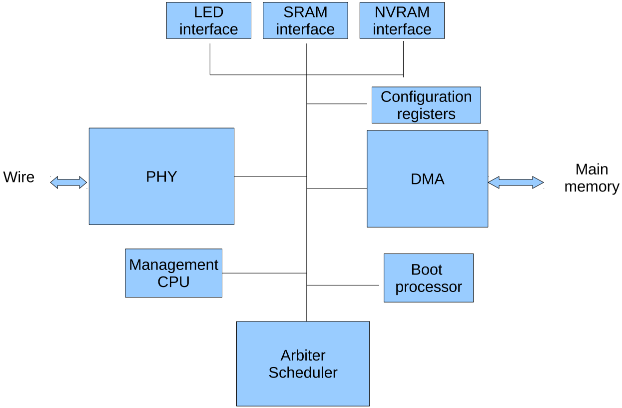
Quite simple in theory

- transfer ethernet frames from the host to the wire
- and vice versa

Increasingly complex in practice...

- advanced capabilities (PXE, TSO...)
- platform administration functions
- active even when OS is down or absent
- runs a firmware on embedded CPU

What is (graphically) a network card?



Intrusion detection model

- Our detection method is anomaly-based
  - The model of normal behavior is based on the NIC's memory layout
  - The memory profile is built empirically, by means of the observed NIC's memory accesses during "normal" network sessions
  - Memory areas used to execute code, read and/or write data are distinguished in the model
  - The card in run in step-by-step (debug) mode during detection
  - Any memory access that is outside the NIC's memory profile is interpreted as an attempt to divert the firmware's control flow
- Heuristics used to detect anomalous memory accesses
  - Step-by-step instruction comparison
  - Step-by-step instruction address checking
  - Shadow return stack

Detection heuristics (1/2)

Step-by-step instruction comparison

- Basically consists in checking that the instruction that is to be run is the same as the reference model's one
- This technique only works if the code is not self modifying (which is the case for the firmware we are considering)

Step-by-step address checking

- Basically consists in checking that the instruction pointer value is consistent
- The network card running code in the heap, in the stack or in the memory scratchpad is indicative of an anomaly

Detection heuristics (2/2)

Shadow call stack

- Basically consists in maintaining a copy of the call stack of the firmware on the host side
- On an identified `CALL`-like instruction, the return address is pushed on the shadow stack
- On an identified `RET`-like instruction, the return address is checked against the saved one

Other heuristics (not implemented)

- Another heuristic could consist in searching for anything that meets the statistical profile of executable code in data area
- This detection technique is prone to false positives

Network Adapter Verification and Integrity checking Solution

We designed our verification framework, NAVIS

- based on card instrumentation
- implements detection heuristics
- prevents control flow modifications

We used:

- Broadcom BCM5754 and BCM5755M network cards
- `ASF` firmware

Preventing confusion:

From now on:

CPU	is the main CPU on the motherboard, running the OS
MIPS	is the management processor on the network controller

Instrumenting the card

- Accessing NIC's memory
    - The NIC's internal memory is mapped in the main memory
    - This mechanism provides access to the firmware running on the NIC

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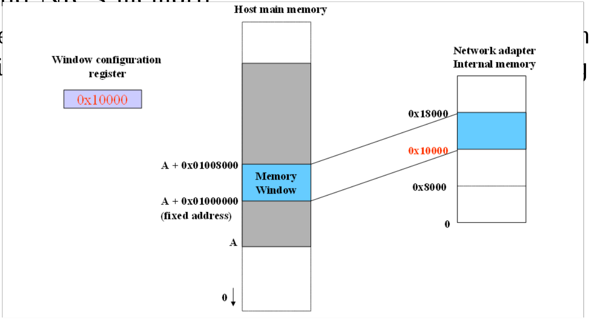

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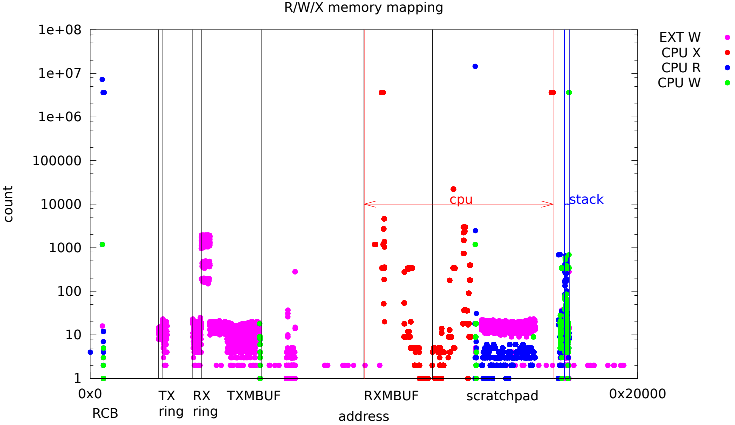
This allows us to monitor the activity of the firmware, detect anomalous behaviours and stop the adapter when a problem is detected

Network controller memory map

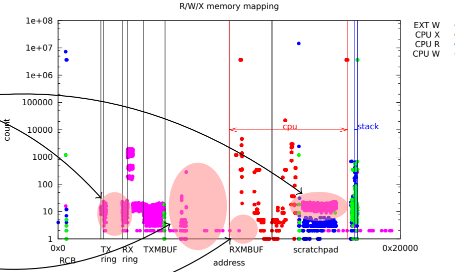
code exec	*instructions executed by the MIPS*
`MIPS` writes	*addresses written by the MIPS (`SH`, `SB`, `SW`)*
`MIPS` reads	*addresses read by the MIPS (`LH`/`LHU`, `LB`/`LBU`, `LW`)*
other writes	*network packets written to the card memory by `DMA` from host and by `PHY` from the wire*



Memory map analysis

External writes

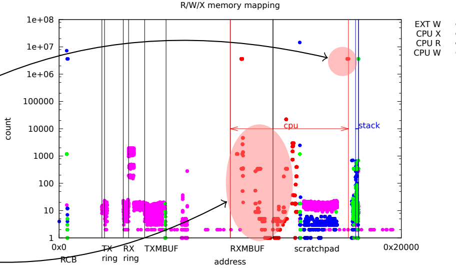
- in `RX/TX` rings and in the *scratchpad* area (traffic from and to the main host)
- in unmapped areas...
- inside the `MIPS` code area!



Memory map analysis

MIPS execution

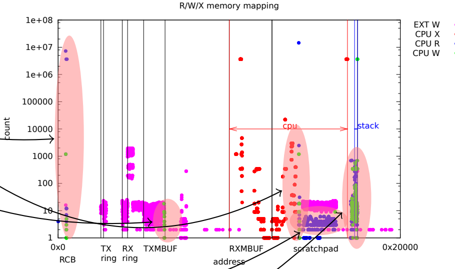
- mostly at the beginning of `scratchpad` plus few instructions at the end



Memory map analysis

MIPS reads/writes

- in the `Rings Control Blocks` and `TXMBUF` (presumably `ASF` traffic)
- in the *scratchpad*, with four different areas:
    - just after the main code area
    - in the packets area (presumably `ASF` traffic)
    - just after the MIPS code area
    - after the MIPS code area, just before *scrachpad* end (the stack)



Challenges in monitoring the MIPS

- Control flow instructions
  - No `CALL`/`RET` instructions on MIPS architecture
  - Fortunately, the firmware code is rather simple
  - Function calls can reliably be inferred from jump instructions (`JAL`) and a specific register (`R31`) used to store return addresses
- Interrupts triggered by the network adapter
  - Cause unexpected changes in the control flow (looks like an attack)
  - The firmware uses a single interrupt handler, starting at a fixed address
  - Return from the interrupt vector is done through register `R27`
  - Dealing with interrupts is manageable by monitoring this behaviour

Summary

we know	▸ where the `MIPS` reads and writes data ▸ where the `MIPS` executes code ▸ how to find function calls and RET
issues	▸ there are external writes to the `MIPS` code area ▸ there are writes in unmapped areas ▸ interrupts make it harder to follow control flow
remarks	▸ no way to enforce *rodata* ▸ no such thing as `NX` on those `MIPS` processor ▸ no segmentation/pagination

This allows to detect any unexpected change in the control flow

- When a return value is modified on the stack
- But data on the stack, heap and scratchpad can still be modified by the attacker.

It works!

We tried the various proof-of-concept attacks we created as part of previous researches

- they are all detected
- an alert is reported in NAVIS
- the network controler is stopped
- one can either reset the card and start fresh,
- or try to investigate in the debugger

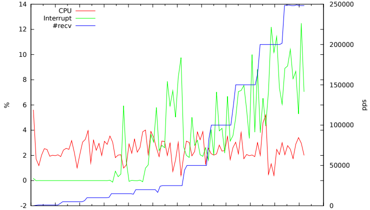
Since we detect control flow modification, other attacks should be detected as well

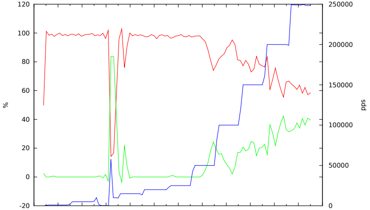
Performance

- The monitoring is expected to have a negative impact on the NIC's performance
    - The MIPS CPU is run in step-by-step mode
    - Various tests are done at each MIPS cycle (*bounds*, *call stack*, etc.)
    - So each MIPS cycle requires many CPU cycles
- Still, performance is not that poor
    - We still manage to achieve gigabit speed…
    - … at the cost of 100% CPU usage on one core (active loop and context switches)
- However, what is really important is
    - packets rate and packet loss
    - when firmware processes packets
    - when NAVIS checks are active (`ASF` traffic)

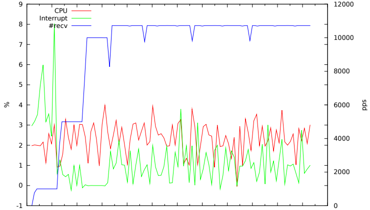
Experimental results

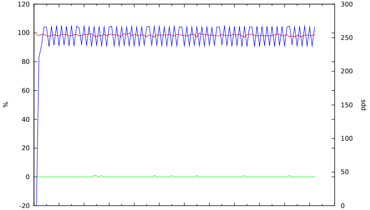
- UDP/9





- UDP/623





Without Navis

With Navis

Limitations of the approach

- The detection model is highly adapter-specific:
  - we tested on BCM5754 and BCM5755M adapters
  - it could be adapted to other Broadcom adapters (provided they use the same kind of firmwares)
  - our concept can be ported to other devices as long as similar debug capabilities are present
- Can an attacker prevent us to control the NIC?
- We cannot prevent arbitrary writes in code area (since standard behavior seems to allow it)
- High processing cost

Conclusion

We proposed NAVIS, a firmware integrity attestation framework:

- firmware integrity attestation is a (very) hard problem
- our proof of concept is highly firmware and adapter specific

NAVIS can detect and prevent most low level attacks on NIC firmware

- But it requires the OS to be trusted.
- And protecting the OS stays the highest priority.

If the embedded devices implement more functions, could they have more protections too?

Questions & Answers

Thank your for your attention

Do you have any question?

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No network cards were harmed in the making of this paper

Bibliography I

[1] Claude Castelluccia, Aurélien Francillon, Daniele Perito, and Claudio Soriente. *On the difficulty of software-based attestation of embedded devices.* In *Proceedings of 16th ACM Conference on Computer and Communications Security*, November 2009.

[2] K. Chen. *Reversing and exploiting an apple firmware update.* BlackHat, 2009.

[3] Guillaume Delugré. *Closer to metal : Reverse ingineering the broadcom netextreme's firmware.* Hack.lu, 2010.

[4] Loïc Duflot and Yves-Alexis Perez. *Can you still trust your network card?* CanSecWest, 2010.

[5] Aurélien Francillon, Claude Castelluccia, Daniele Perito, and Claudio Soriente. *Comments on "refutation of on the difficulty of software based attestation of embedded devices".* –, 2010.

[6] Alexandre Gazet. *Sticky fingers & kbc custom shop.* –, 2011.

[7] Yanlin Li, Jonathan M. McCune, and Adrian Perrig. *SBAP: Software-Based Attestation for Peripherals.* In *Proceedings of the 3rd International Conference on Trust and Trustworthy Computing (Trust 2010)*, June 2010.

[8] Yanlin Li, Jonathan M. McCune, and Adrian Perrig. *VIPER: Verifying the integrity of peripheral's firmware.* In *Proceedings of CCS'11*, 2011.

[9] Alfredo Ortega and Anibal Sacco. *Deactivate the rootkit.* BlackHat, 2009.

Bibliography II

[10] Adrian Perrig and Leendert Van Doorn. *Refutation of "on the difficulty of software based attestation of embedded devices".* –, 2010.

[11] Fernand L. Sang, Eric Lacombe, Vincent Nicomette, and Yves Deswarte. *Exploiting an I/OMMU vulnerability.* In *MALWARE '10: 5th International Conference on Malicious and Unwanted Software*, pages 7–14, 2010.

[12] Arrigo Triulzi. *Taking NIC backdoors to the next level.* CanSecWest, 2010.

[13] Ralf-Philipp Weinmann. *All Your Baseband Are Belong To Us.* CCC, 2010.