Can you still trust your network card?

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Modern network cards

They do not only connect the host to the network.

- Hardware architectures are complex:
  - several processors,
  - different kind of memories,
  - multiple network interfaces;
- Embedded softwares (firmwares) do more than you think:
  - remote administration: ASF, IPMI, AMT, etc,
  - TCP segmentation offloading,
  - radio with temporal constraints: GSM, 802.11, etc.

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Impacts on security

If an attacker can execute arbitrary code on the card, she can do virtually anything:

- stop processing packets;
- drop some packets;
- ARP/DNS cache poisoning;
- implement SSLstrip-like attacks;
- attacks hosts on the LAN;
- replace the firmware;
- attack the host (read/write access to the main memory).

A "must read" on this topic:
Arrigo Triulzi, PacSec08, "Project Maux Mk.II"

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What will be described today

We will present:

- architectures of modern network cards;
- remote administration protocols used in these cards;
- an actual vulnerability that we discovered;
- tools developed to debug a *Broadcom NetXtreme* card;
- exploitation proof of concept and demo;
- mitigations and workarounds to this attack.

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What won't be described today

This is not about:

- driver bugs;
- OS vulnerabilities.

And please note that:

- we won't provide the network packets and the tools used in the demo;
- we worked with the vendors and they issued a patch for the vulnerability.
    - `CVE-2010-0104`: *HP Small Form Factor or Microtower PC with Broadcom Integrated NIC Firmware, Remote Execution of Arbitrary Code*

http://www.ssi.gouv.fr/trustnetworkcard

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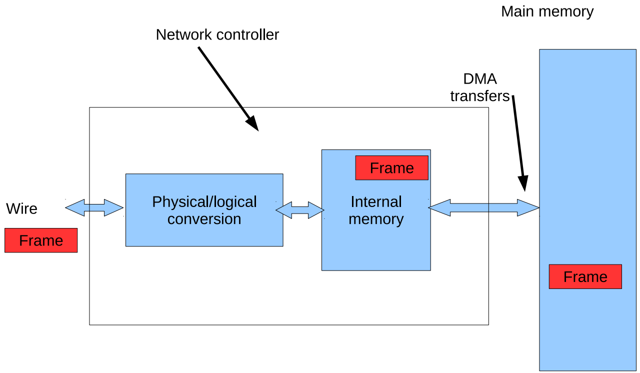
Internal architecture of a network card

- PHY: send and receive signals on the wire;
- DMA-engine: exchange packets with the host;
- negotiation and link control (speed, duplex), etc.



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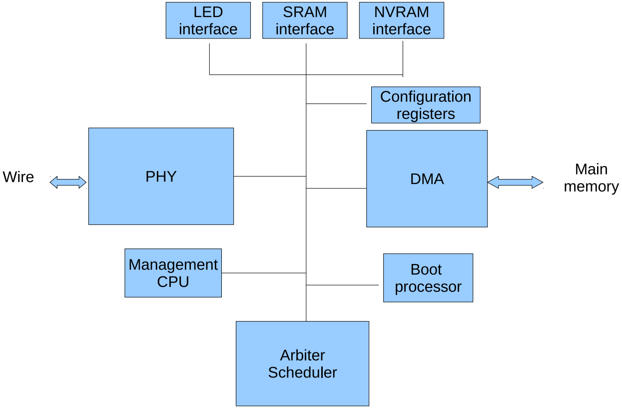
Internal architecture of NetXtreme network card

- performs various operations on packets;
- offloads work from host;
- needs hardware and software to do that;
- runs as an intercepting proxy.



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RX RISC

An on-chip RISC processor is provided for running value-added firmware that can be used for ***custom frame processing****. The on-chip RISC operates independently of all the architectural blocks; essentially, RISC is available for the* ***auxiliary processing of data streams.***

- a `MIPS CPU` on the card;
- it has access to major components:
  - shared memory,
  - incoming and outgoing packets,
  - `PCI Configuration Space`,
  - `SMBus`;
- it executes a *firmware*.

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The firmware in the NetXtreme

Different firmwares:

- ASF (Alert Standard Format protocol);
- TSO (TCP Segmentation Offloading).

The firmware is:

- loaded from an EEPROM;
- or by the driver from the filesystem:
  - Linux driver only has TSO,
  - Windows drivers rarely have a firmware,
  - the firmware seems protected;
- loaded to memory (SRAM) during execution.

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Internal memory

- the card internal memory is mapped to the host one;
- internal memory can be accessed through a 32kb window;
- this window can be moved to read the whole internal memory space from the host.

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Alert Standard Format (ASF) 1.0 1/3

ASF

- transmits alerts/events using the network:
  - hard disks failures, BIOS errors, ...
  - heartbeats ("machine is up");
- must operate if everything else fails (dead hard disks, OS).

The network card receives events from others devices using the SMBus (*System Management Bus*).

RMCP

- ASF uses a protocol called *Remote Management and Control Protocol*;
- RMCP can query system state;
- RMCP allows to remotely start, stop or reboot computers.

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Alert Standard Format (ASF) 1.0 (2/3)

- firmware parameters must be configured: IP address, netmask, heartbeats frequency,
  - a tool is provided by network cards vendors;
- a specific ACPI table is used by ASF;
- ASF can be deactivated from the BIOS on some hardware;
- at least one boot on an ACPI-enabled OS is mandatory.

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ASF 1.0 (3/3)

Security

- no security interfaces;
- vendors are discouraged to implement their own, proprietary security interface;
- security issues should be addressed at network infrastructure level.

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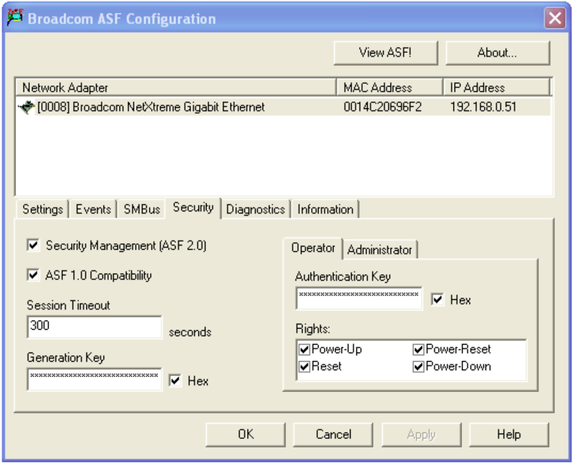
ASF configuration



- IP addresses;
- RMCP;
- permissions;

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Alert Standard Format (ASF) 2.0

ASF 2.0 adds a new protocol: RSP

- RMCP security-extensions protocol;
- adds authentication and integrity protection;
- no encryption.

This presentation focuses on ASF 2.0.

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RMCP in ASF 2.0

- messages are sent over UDP;
- traffic must be either sent on:
  - the legacy port 623/udp: no authentication, no integrity,
  - the secure port 664/udp: RMCP messages are carried inside *RMCP Security-Extensions Protocol* (RSP);
- the network card grabs traffic on these ports, analyzes RMCP packets, and replies to queries.

The network card must implement the following stack: IP/UDP/RSP/RMCP.

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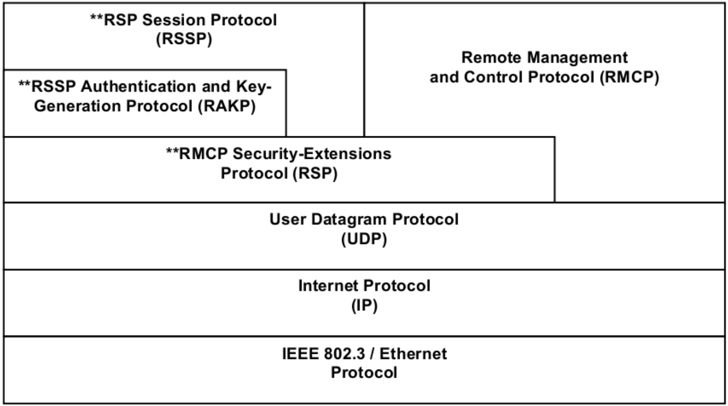
Protocols stacks



RMCP Security-Extensions Protocol (RSP)

- RSP adds mutual authentication of the remote console and the client;
  - the **console** is the management device used by the administrator,
  - the **client** is the remote workstation;
- messages are authenticated using pre-shared HMAC-SHA1 keys;
- in order to send a message on the secure port, the console must:
  - open a session,
  - negociate a session key (three messages are exchanged),
  - send the RMCP message protected with the sessions key over RSP.

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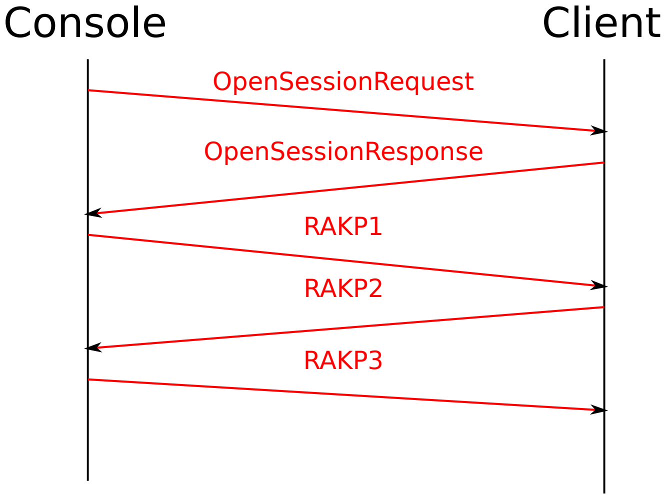
RSP session protocol (RSSP)



The RMCP messages

- `Presence Ping` / `Presence Pong`;
- `CapabilitiesRequest` / `CapabilitiesResponse`;
  describe which operations are possible on the legacy and the secure ports;
- `System State Request` / `System State Response`;
  ask system about status, last boot medium etc.
- startup request (device can be specified: `PXE`, hard disk, `CD-ROM`);
- reboot request;
- stop request.

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Status of RMCP support

Some hardware with ASF support that we tested:

- HP Compaq dc7600
  - on the secure port, start/reboot/stop messages are processed;
- DELL Latitude D530 and Precision T5400
  - CapabilitiesRequest messages are processed,
  - CapabilitiesReply messages indicate that no remote administration function is supported.

Remarks

- no vendor enabled remote administration on the legacy port;
- why do some vendors disable administration functions but still implement RMCP and SMBus functions?

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Card's behavior when using ASF

When it receives a packet, the card

- intercepts the packet;
- before transmitting it to the OS;
- checks if it is a RMCP packet;
- process it:
  - open/close session,
  - send system state informations,
  - perform system administration tasks,
  - the packet is **NOT** transmitted to the host.

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Protocol security (1/2)

Potential issues

- protocol uses 160bit pre-shared keys, which means all clients might have the same keys;
- messages are integrity protected but the integrity pattern does not include message ID;
- in order to act as the *console*, an attacker just has to send a $\texttt{RAKP}_3$ with a valid HMAC.

Exploitation

- is it possible to forge the HMAC?
- can the client act as a integrity oracle?

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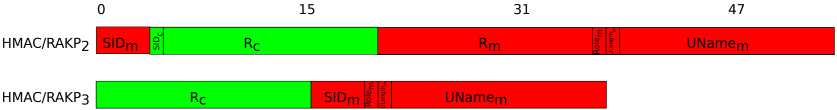
Protocol security (2/2)

Not so easy

- only two concurrent sessions on the implementation we tested;
- not all fields are under the attacker's control;
- fields size problems.



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Implementation problems (1/2)

Interesting fields under the attacker's control

- management console username ($RAKP_1$ message);
- management console session ID (`Open Session Request`).

Trying to play with them, messing with

- size;
- content.

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Implementation problems (2/2)

Username

- specifications limit the size to 16 chars, without `NULL`;
- the username size is coded using a 1 byte field.

What if we don't play nice?

- "the card crashes";
- the host can only send Ethernet frames but not receive them.

What did exactly happen?

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Proof of concept

- Is the vulnerability serious?
- What are the direct and indirect consequences?
- How can we build a *proof of concept*?

Speaker switch

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Instrumenting the card (1/2)

How did we find out what happened?

- what is really crashing?
- how is it crashing?

Using the NetXtreme specifications

- public specs available for open-source developers;
- describe the internal card behavior;
- give informations about `RX RISC` components.

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Instrumenting the card (2/2)

How to debug the `RX RISC`? We need to:

- follow the execution flow;
- know registers contents;
- know why the `CPU` stops;
- trace data.

We need a *network card debugger*.

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What information can we retrieve from the card?

Specifications and experiments say we have access to:

- `RX RISC` mode register;
- `RX RISC` state register;
- `RX RISC` program counter;
- `RX RISC` hardware breakpoint register;
- some general registers.

We can use this knowledge to build that debugger.

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Our homemade debugger:

- uses information from mapped registers;
- runs in step-by-step mode;
- can perform register/memory tracking;
- can break on register/memory access;
- can do some pattern matching.

Help

```
What should I do next (h for help)? h
Usage:
'a' -> Advance n steps                        'T' -> Track register
's' -> Advance 1 step                         'L' -> Track memory address
't' -> Trace                                  'Z' -> Track specific memory zone access
'c' -> Continue                               'I' -> Track pattern in memory
'C' -> Continue (step-by-step                 'P' -> Track pattern
'g' -> Break on instruction                   'x' -> Clear tracking
'R' -> Break on pattern in register           'f' -> Find pattern in internal memory
'S' -> Break on pattern in stack              'F' -> Find pattern in external memory
'H' -> Break on pattern in internal memory    'A' -> Find all patterns in external memory
'M' -> Break on pattern in external memory    'd' -> Display memory address
'n' -> Break on next pattern in stack         'D' -> Display memory area
'l' -> Break on specific memory access        'w' -> Write a word to memory address
'm' -> Break on any memory access             'r' -> Reset CPU
'j' -> Break on register write                'q' -> Quit
'i' -> Break on instruction
```

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CPU

```
******** Instruction
Instruction = 3c020001 LUI r2 = 00010000
Last memory access = 00000000
******** CPU Status Registers ******
RXPC   = 00011078 RXHWBRK = 0000001d
RXMODE = 00009db0 RXSTATE = 80001400
```

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General registers

```
******** CPU Registers ************************************
$0  = 00000000 $1  = 00010000 $2  = 00000000 $3  = 40000000
$4  = 0001b4b8 $5  = 0001b8e6 $6  = 00000000 $7  = 0001bfc4
$8  = 00000040 $9  = 00000050 $10 = 0001b8bc $11 = 0001bfc0
$12 = 80000000 $13 = 00000001 $14 = 00000000 $15 = ffffffbf
$16 = a4020000 $17 = aaaaaaaa $18 = 00000000 $19 = 0001af48
$20 = 0000ad60 $21 = 018004f1 $22 = 000000fc $23 = 00010000
$24 = ffffffff $25 = 80000000 $26 = 00000b50 $27 = 00011104
$28 = c0000000 $29 = 0001bfd8 $30 = 0001c000 $31 = 000111f8
```

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Stack

```
******** Stack *****************************
Stack pointer: 0001bfd8 (max) stack size: 10
Stack bottom:  0001c000
********************************************
0001bffc:73ffffff  0001bfe8:00010e00
0001bff8:00010044  0001bfe4:0001a918
0001bff4:0001a000  0001bfe0:0000ad60
0001bff0:0000ad64  0001bfdc:0001a000
0001bfec:0001a80c  0001bfd8:00010b3c
```

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Why does the card crash?

`RX RISC` state register provides useful information:

1. `bad memory alignment`
2. `invalid instruction fetch` (jump to invalid location);
3. `invalid data access` (load/store in invalid location);
4. `invalid instruction`;

Points 2 and 4 can mean direct flow execution redirection.
Points 1 and 3 can mean indirect flow execution redirection (try to overwrite a return address in the stack).

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Changing the execution flow

When the `RX RISC` CPU is crashing, an attacker needs to:

- find the source of the data;
- tune it to fit her needs.

Trials and errors

We managed to:

- make the *username* field overflow;
- overwrite a return address in the stack with an address under our control.

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Proof of concept code injection (1/2)

On this particular NIC and firmware version, an attacker is able to perform arbitrary code execution:

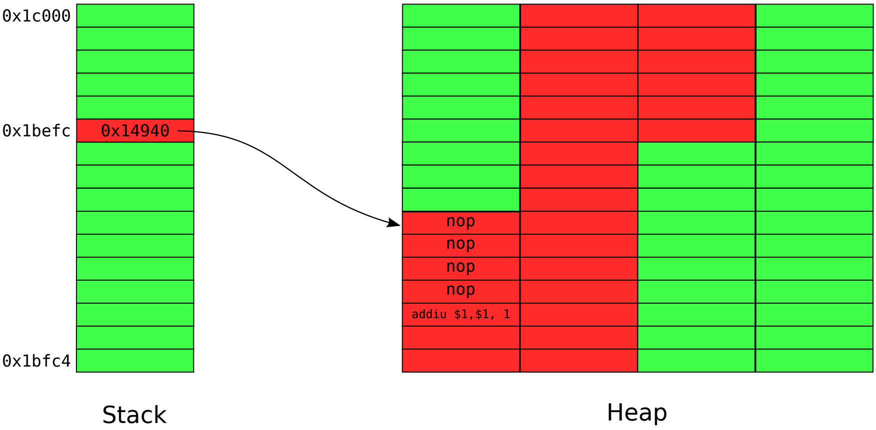
Initial jump

- an attacker can overwrite a return address in the stack;
- she can find a stable (for a firmware version) memory address for *username*;
- she can put exploit code in *username* and jump there.

Stage 1

- *username* is 255 chars (minus padding), not much instructions;
- but the attacker has access to network buffers;
- she can put code in a previously sent packet and jump there.

Exploit and stage 1



Proof of concept code injection (2/2)

stage 2

- size virtually unlimited;
- sent like a normal packet before the exploit;
- prepended by a magic number so `stage 1` can find it.

Now the attacker can:

- run arbitrary code on the `RX RISC`;
- provide new code using simple packets;
- rewrite the firmware if needed;
- ...

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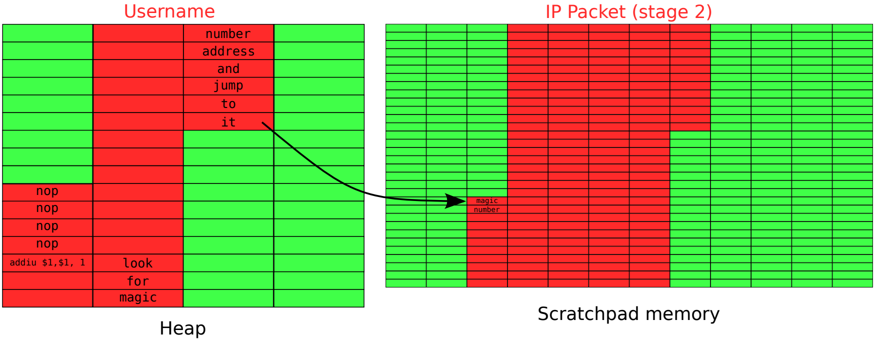
Stage 2


Username
number
address
and
jump
to
it
nop
nop
nop
nop
addiu $1,$1, 1
look
for
magic
Heap
IP Packet (stage 2)
magic
number
Scratchpad memory

Man in the middle

Every packet ends up in the card memory:

- received packets before reaching the host;
- sent packets before being emitted on the wire.

Play

- reroute DNS traffic;
- reroute *all* traffic;
- modify TLS negotiations;
- perform any conceivable MITM stealthily.

Remote management

Remember DELL disabled remote management?

- but the controller is connected to the SMBus;
- ASF! description table is present with the remote control functions;
- the exploit send messages to the SMBus;
- therefore it can perform *power-up*, *power-down*, *power-cycle*, ...

It can be reimplemented!

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Take-over the host

The network card:

- is on the PCI/PCI-Express bus;
- can read/write to PCI configuration space;
- has Direct Memory Access (DMA) to the host.

The attacker taking over the NIC can read and write to main host memory!

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Using DMA

DMA transfers

- NIC and host share network packets using DMA;
- meta-data (NIC address, host address, size) are stored in special structures, the *buffer descriptors*.

proof of concept code: write to main memory

- write an host address to a buffer descriptor address field in the NIC;
- send packets;
- packet is written to the main memory at given address.

(almost) reliable.

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OS dependent

- like all DMA-based attacks;
- need to get around IOMMU;
- need to find out where to read/write;
- need to trigger the code execution.

- for the proof of concept, we used Linux (because we know how it works);
- same would work for any other OS;
- nice trick, configure a new mac address on the NIC: 90:90:90:90:90:90.

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Demonstration

What we do in the demo:

- write some code at address 0 to run a remote shell;
- hook ourselves into `icmp_rcv` to jump at address 0;
- send a *magic ping*.

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Countermeasures

- use a patched firmware;
- deactivate ASF (not only in the BIOS);
- filter ASF and RMCP UDP ports;
- use an IOMMU on a supported OS;
- deactivate remote administration protocols, or
- reserve remote administration to safe/separated networks.
  - nobody ever enabled ASF on a laptop connected to Internet anyway
  - is it really safe to assume that?

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Conclusion

This vulnerability might seem scary, however remember:

- few cards support ASF;
- fewer cards enable ASF.

But,

- ASF is quite simple:
  - over UDP,
  - few cryptographic algorithms,
  - limited number of sessions,
  - no interaction with the network;
- AMT, IPMI, and the other remote management protocols are more complex:
  - over TCP,
  - heavy use of *webservices* (XML-RPC, SOAP, ...),
  - interactions with the whole network infrastructure (*Active Directory*, *Kerberos*, ...).

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Conclusion (2/2)

- more and more devices require firmwares:
  - network cards,
  - wireless network cards,
  - GSM and UMTS chipsets,
  - RAID controllers;
- with common characteristics:
  - no source code available,
  - close to the hardware,
  - possible access to the outside world (network cards),
  - real-time constraints.

More issues are likely to appear in the future.
It is time to develop simpler network cards and smaller drivers.

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Question & answers

?

FAQ are available at

http://www.ssi.gouv.fr/trustnetworkcard

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