Security Enhanced Linux on Embedded Systems: a Hardware-accelerated Implementation

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Outline

- Motivations
- Overview of SELinux
- SELinux on Embedded Systems
- Hardware-assisted SELinux
- Implementation
- Experimental results

Motivations (1/3)

- Security has gained importance in the embedded systems world
- Computing and communication increasingly pervade our lives:
  - security and protection of sensitive data are extremely important
- Embedded Systems present several unique security challenges:
  - Resource constrained
  - Often very portable

Motivations (2/3)

- Vulnerability to attacks increases with the functionalities

- Possible attacks from:
  - Cellular networks
  - Bluetooth
  - Network connection
  - USB
  - ...
- Threats to:
  - data confidentiality
  - data integrity
  - availability of data and services

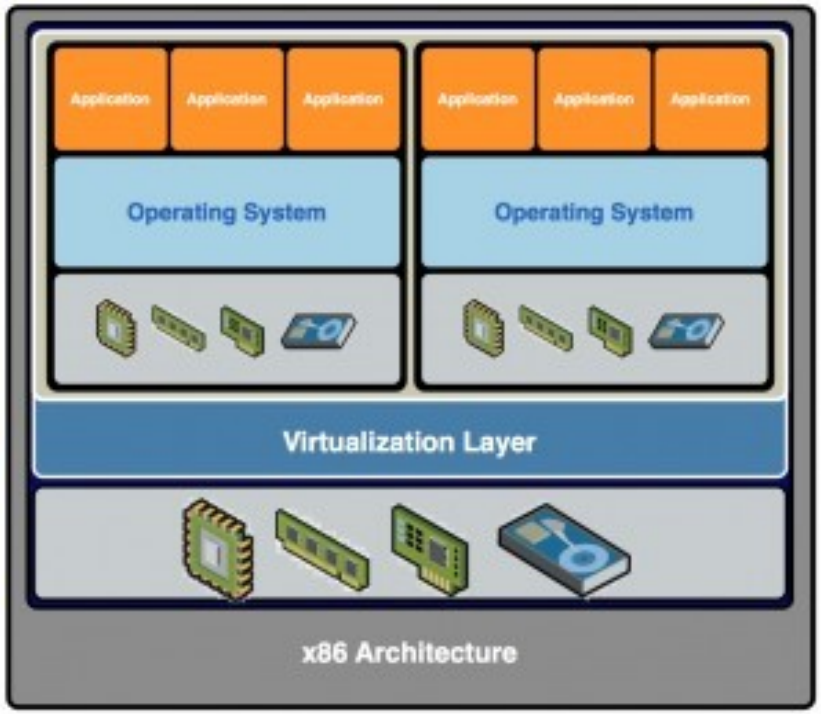
Motivations (3/3)

- Security solutions available for computers are:
  - often not scalable to ES
  - partially effective
  - rarely employed by final users

Process Isolation

- Restrict access of processes to system resources:
  - It greatly limits the effects of security holes in the software.
- It can be implemented in different ways:
  - Virtualization
  - Fine-grain access control on resources

Virtualization



[http://www.supportsd.com/services/virtualization]

- Should be configured properly to provide secure isolation
- Resource demanding:
  - Not suitable for most embedded systems

Fine-grain access control on resources

- Allows controlling the access by processes to system resources
  - Files
  - Devices
  - Memory locations
  - Network sockets
  - ...
- Allows implementing sandboxing:
  - Each group of applications are confined in a different “environment”
    - No access to resources of other processes

Overview of SELinux (1/2)

- Designed by National Security Agency
- Introduced in 2001
- Included from 2003 as a standard kernel module in Linux
  - e.g., in Red Hat and Fedora Linux it is enabled by default
- Flexible mandatory method for controlling accesses to all the resources by processes:
  - Supplements Linux with a Mandatory Access Control (MAC)
    - Linux implements Discretionary access Control: Users may give or revoke access privileges to their own objects

Overview of SELinux (2/2)

- It defines the access and transition rights of:
  - Users
  - Applications
  - Processes
  - Files
- It governs the interactions of these entities:
  - Based on a well-defined security policy
    - Set of **rules**
    - Written in accordance with the *principle of least privilege*: allowed actions must be explicitly defined

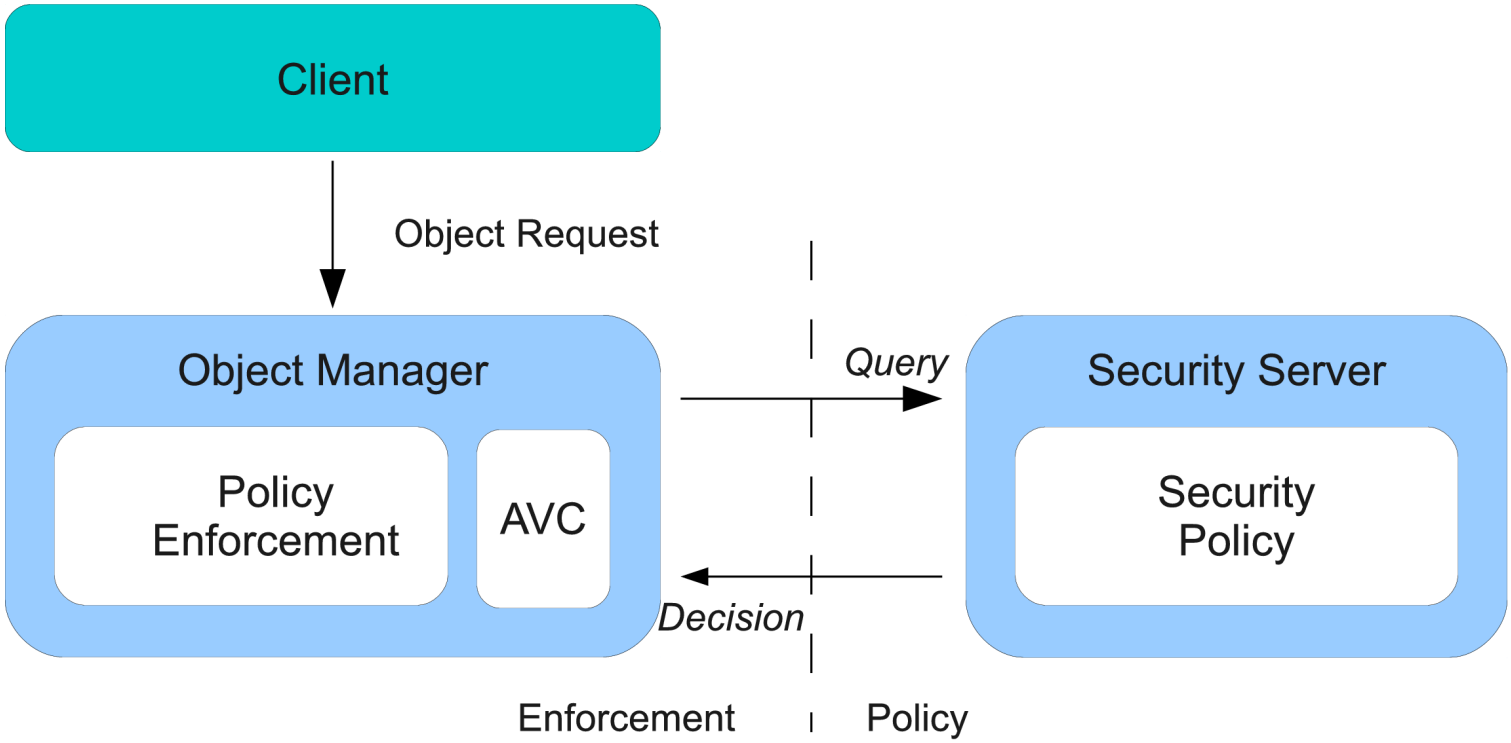
SELinux: elements (1/2)

- Subject:
  - The system element requesting access to a resource:
    - Typically a process
- Object:
  - The resource to be accessed:
    - a file, a network socket, a device, …
  - Objects are divided in classes:
    - Specify the kind of object

SELinux: elements (2/2)

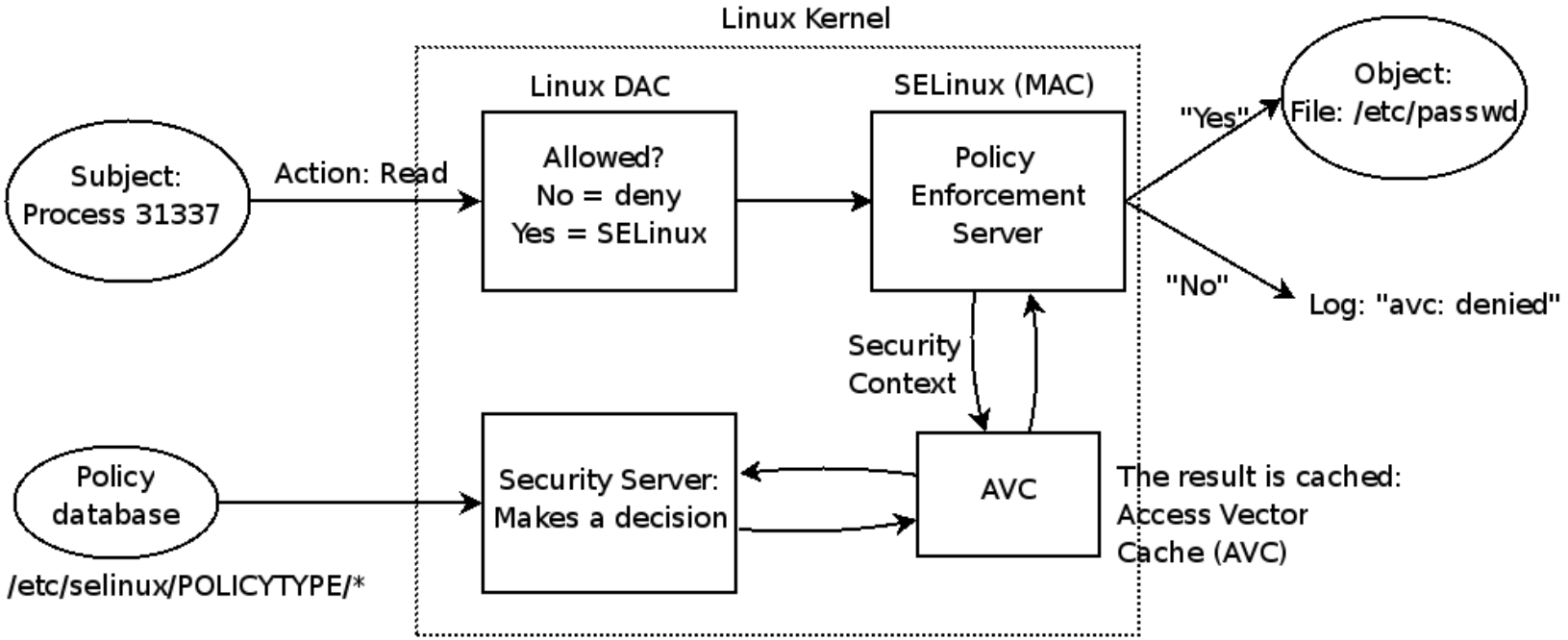
- Security server:
  - Takes decisions (allowed/not allowed) on the requested actions
  - Contains the **SELinux Policy:**
    - Each rule contains the triple subject, object, object class, and the associated access vector
    - The policy database is managed as a common single linked list hash table; the key is a concatenation of the subject identifier, the target identifier, and the object class
- Object Manager:
  - Queries the Security Server
  - Caches the decisions of the Security Server:
    - **Access Vector Cache** (AVC), managed in the same way as the policy database
  - Enforces the access decisions

SELinux Architecture



Clean separation between policy enforcement code and decision-making core

SELinux – Query Example



taken from: *Lars Strand, "RHEL5 SELinux: A benchmark"*
http://blog.larsstrand.org/article.php?story=RHEL5-SELinux-Benchmark

SELinux in Embedded Systems

- Overhead not negligible in terms of CPU usage and memory [1][2][3]:
  - Overhead on single operations might be high
  - Overhead on full applications depends on the application:
    - up to 10% for Apache
    - an average of 7% on the server activities
    - up to 66% for I/O intensive applications on embedded systems
    - Up to 8% for non-I/O intensive applications

Operation	Overhead (%)
Lmbench Null read	130
Lmbench Null write	147
Lmbench Create	168
Lmbench TCP	22
Unixbench 256B read	67
Unixbench 1024B read	44
Unixbench 4096B read	16

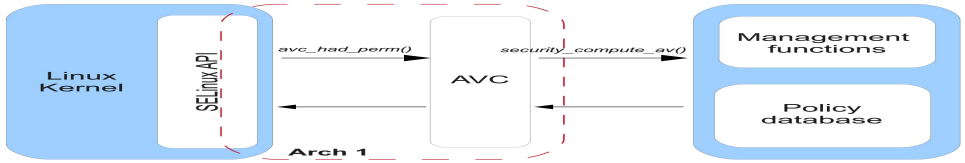
[1] Y. Nakamura et al, SELinux for Consumer Electronic Devices, Linux Symposium 2008
[2] A. Shabtai et al, Securing Android-Powered Mobile Devices Using SELinux, IEEE Secury and Privacy, 2010
[3] *L. Strand, "RHEL5 SELinux: A benchmark"*

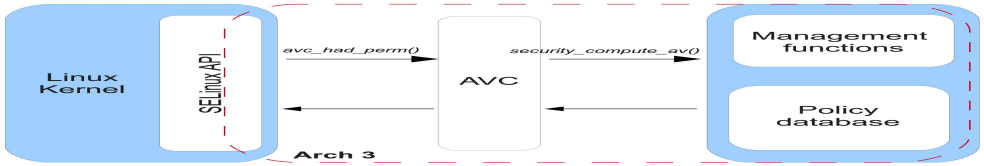
SELinux in ES – previous work

- Previous work focused on:
  - reducing the size of policies by removing unnecessary configurations
  - tuning kernel and userland by removing unneeded functions
  - reducing memory usage by removing non-required data structures from kernel
- Selinux was ported to Android devices and to Nokia 770 internet tablet
- Security Enhanced Android released by NSA

- In our work we decrease the performances overhead:
  - Lower energy overhead
  - Lower computational cost
  - No modifications on memory consumption
  - No modifications to the architecture of SELinux

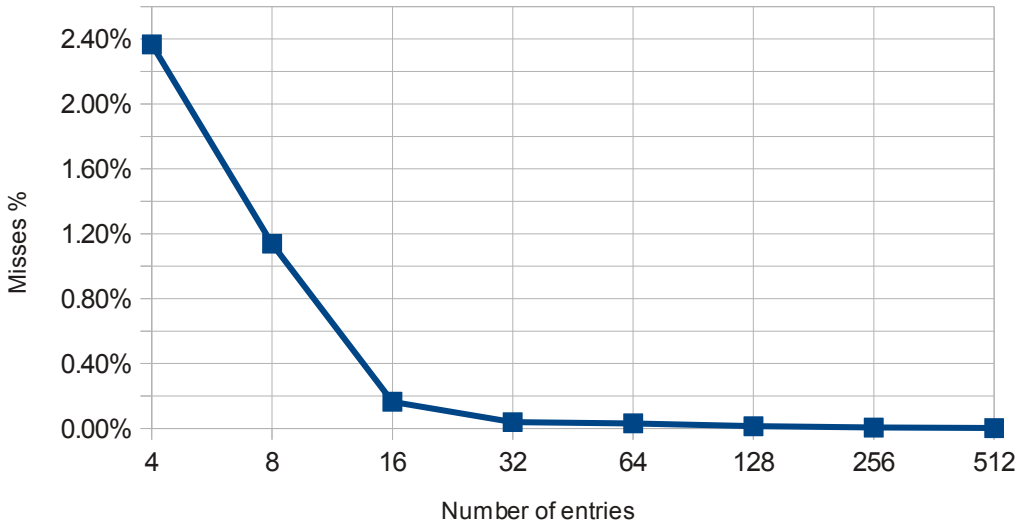
Hardware-assisted SELinux – Possible architectures





Hardware-assisted SELinux

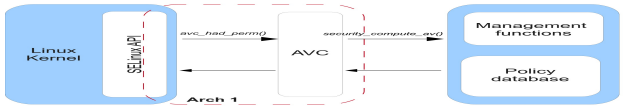
- Main source of overhead is in the policy lookup operations:
  - Done at each access!
- Most of the lookups are normally executed in the AVC

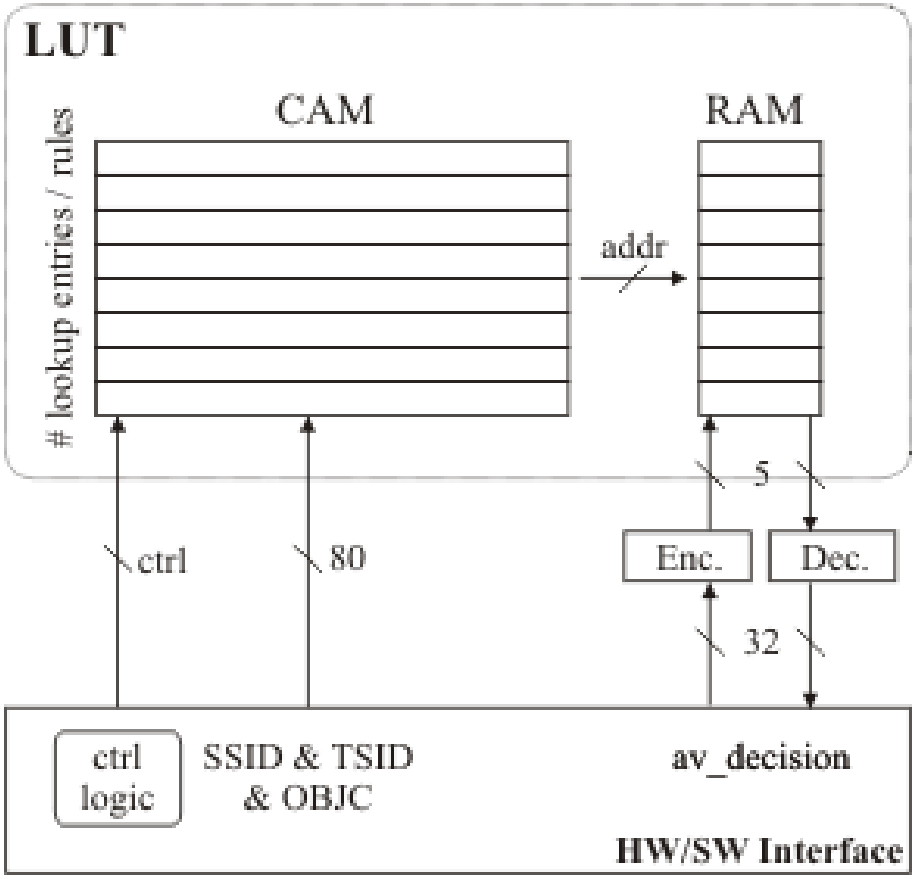


Tests on mplayer playing a mp3 file over internet

The AVC can be implemented in hardware to reduce the time/energy overhead

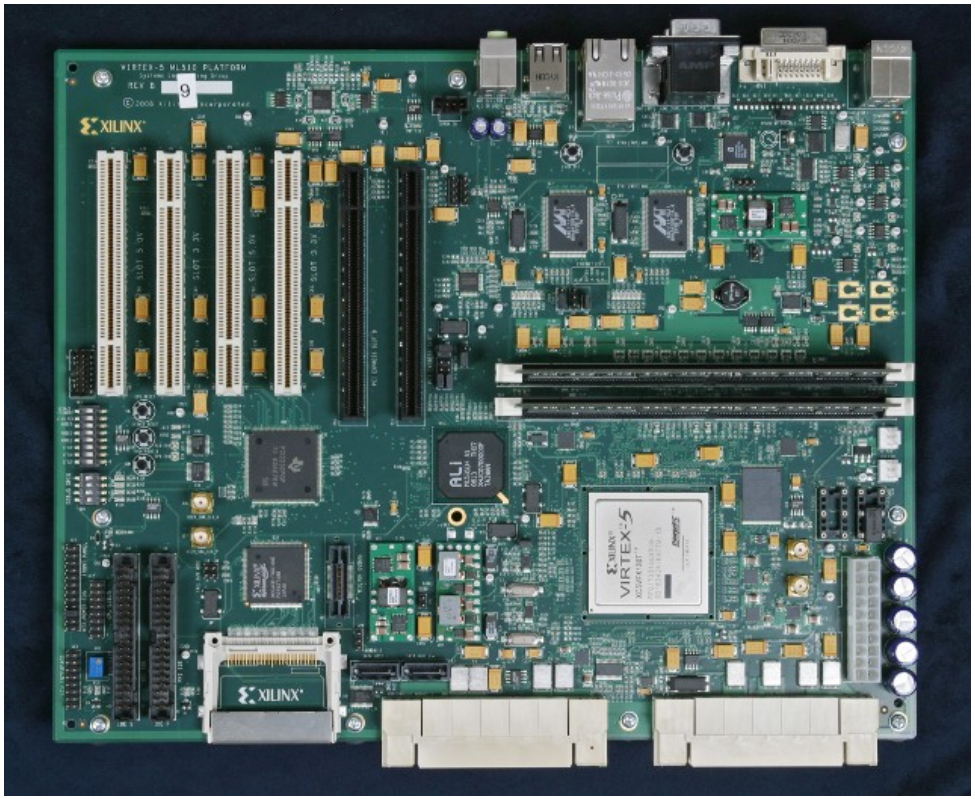
Hardware AVC (HAVC)





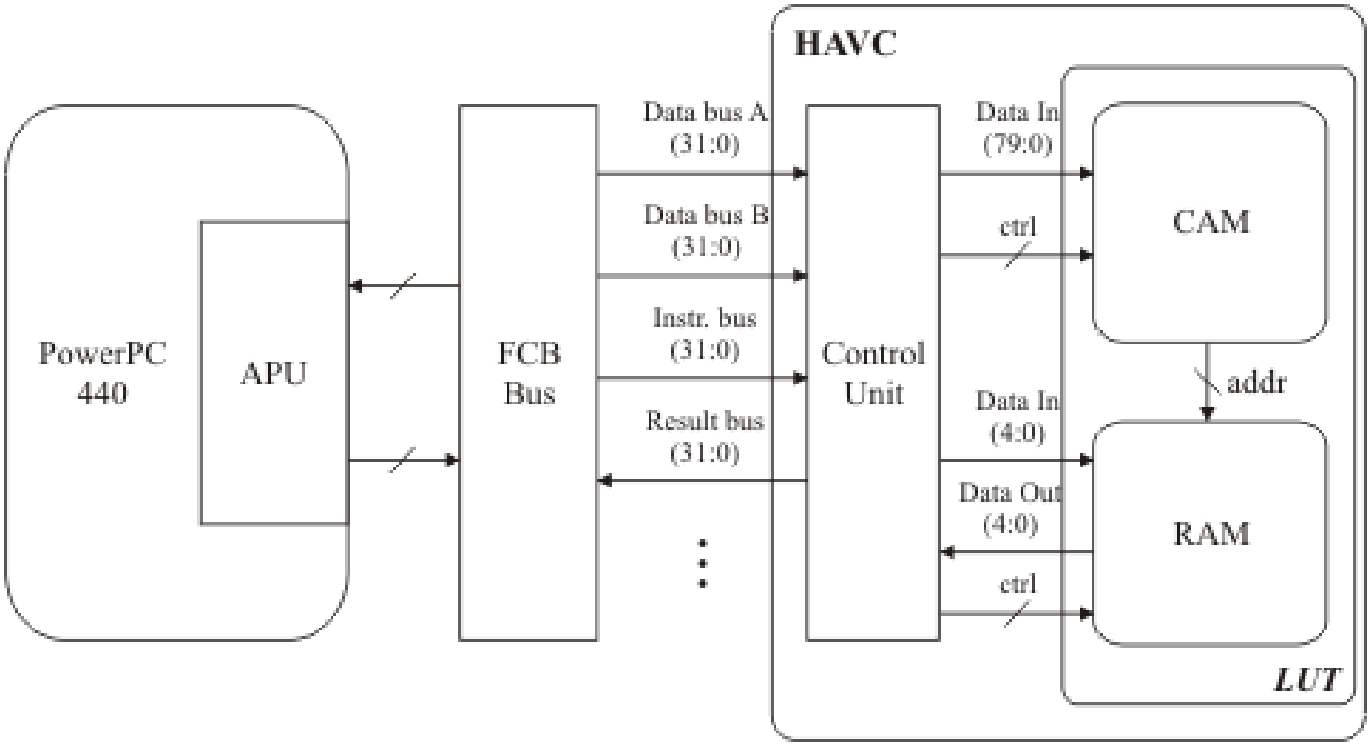
- Mainly composed of a LUT
- The CAM stores keys to be looked up when performing access control
- The RAM stores the encoded access rights for the key:
  - Different encoding used to reduce memory occupation

Implementation (1/2)



- Prototype system implemented on a Xilinx ML510:
  - Linux (kernel 2.6.34) running on the onboard PowerPC 440
  - HAVC implemented on the Xilinx Virtex V FPGA

Implementation (2/2)



- AVC query and insert added as new instructions
- Use of Auxiliary Processor Unit (APU) for implementing the HW API
- The Control Unit:
  - Implements a FSM
  - Controls the execution of queries/insertions

Integration with the OS

- SELinux code modified for using the HAVC
- Added a hardware API for SELinux
- Proper interfaces for the hardware accelerator added by modifying the related function calls:
  - In *avc_has_perm()* the *avc_lookup()* function substituted with a call to the HW API
  - In *avc_has_perm()* the *avc_insert()* function substituted with a call to the HW API

Results – Single lookup cost

Benchmark	*avc_lookup()* (SW)	Impr. (%)	*avc_insert()* (SW)	Impr. (%)
bitcount	315.70	95.6	3,476.53	99.0
blowfish (enc/dec)	535.65	97.4	3,460.72	99.0
susan	547.58	97.4	3,466.23	99.0
syscall write	497.76	97.2	3,447.06	99.0
syscall fstat	408.97	96.6	3,458.65	99.0
pipe latency	356.46	96.1	3,478.92	99.0

Results – Overhead on benchmarks

Benchmark		SW SELinux overhead (%)	HW SELinux overhead (%)
MiBench	bitcount	0.7	0.001
	blowfish (enc/dec)	1.4	0.1
	susan	0.46	0.0043
	stringsearch	2.9	0.01
	basicmath	0.4	0.0087
	jpeg (enc/dec)	2.7	0.7
	ADPCM (enc)	8.1	3.7
LMBench	syscall write	43.0	28.1
	syscall stat	61.1	26.2
	syscall fstat	66.2	21.0
	syscall open/close	46.7	18.1
	signal handler install.	1.8	0.1
	signal handler overhead	18.9	3.3
	protection fault	21.4	4.1
	pipe latency	29.0	4.0
	UNIX socket	17.8	8.53

Results – Area and Energy Measurements

- CACTI was used for estimating the area of:
  - RAM
  - CAM
- Synopsys Design Compiler was used for estimating the area of the other components of the HAVC
- Wattch used to estimate energy consumption of
  - software-only SELinux
  - hardware-accelerated SELinux:
    - HAVC instructions were added to the instruction set
    - Energy consumption of a single HAVC instruction evaluated through CACTI and Synopsys

Results – Area

# Entries in HAVC	Area (mm2)
32	0.0342
64	0.0537
128	0.0957
256	0.1256

- A HAVC with 64 entries uses an area that is 2.5% the one of a PowerPC 405-F6 implemented on a 90nm technology.

Results - Energy

Function	Average Energy (nJ)
SW-only lookup	826
SW-only insert	2,923
HW-SW lookup	0.0106
HW-SW insert	0.0107

- Energy consumption for single queries/inserts is orders of magnitude lower when the hardware accelerator is used.

Conclusions

- We proposed a solution for reducing the performance overhead due to SELinux
- We tested the solution with good performances by implementing it on a FPGA-based platform
- We evaluated area and energy of an ASIC implementation

Future Work

- Write a policy targeted for embedded systems:
  - Generic policy
  - Policy for sandboxing of non-trusted applications
- Improve the management of the HAVC
- Optimize the architecture of the accelerator for multicore/multiprocessors
- Investigate the adoption of the accelerator for PCs and servers.

Thanks for your attention!

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