Scalable Intrusion Detection System in the Cloud

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Heterogeneous VM Replication: A New Approach to Intrusion Detection, Active Response, and Recovery in Cloud Data Centers

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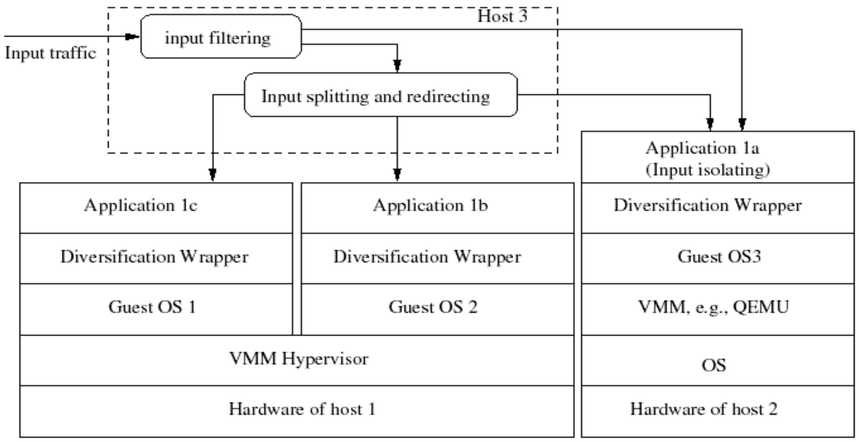
Project Goal

- Proactive defense techniques needed to combat against emerging and evolving cyber threats against clouds.
- This research focuses on development of a Moving Target Defense technique, H-VM-R (Heterogeneous VM Replication), to detect and prevent intrusion attempts in cloud data centers.

Research Approach

- Develop H-VM-R based intrusion detection approach by comparing heterogeneous VM images resulting from same execution history
- Develop cost-effective response by proactively setting up standby VM replicas
- Develop migration technique to move compromised VM replica to clean yet heterogeneous VM replica.

H-VM-R Architecture



Work Accomplished

- Developed and implemented Heterdevice system prototype to detect resource starvation attacks from compromised drivers (RAID 2012)
- Developed and implemented kernel-level rootkit detection system for cloud environment (in submission)
- Established cloud data center testbed at TSU comprising of 50 Dell PowerEdge M610 servers running OpenStack and Hadoop distributed computing platform

Kernel-Level RootKit Detection System in Cloud

- Cloud Computing enable ubiquitous access to data and applications
- Cloud security issues have gained traction due to vulnerabilities in low level operating systems and virtual machine implementations resulting in novel denial-of-service attacks [Liu, CCSW 2010]
- Kernel-Level Rootkits has the potential to inflict maximum damage and can launch stealth attacks, which can be difficult to detect or eliminate by the administrator.
- Need for an efficient, scalable and easy to deploy Kernel- rootkits detection system in the cloud

Kernel-Level RootKit Detection System in Cloud

- **Several Kernel-level rootkit detection systems to protect hypervisors have been reported**
- **VMWatcher [Jiang, CCS 08] and Lares [Payne, S&P 08] constructing semantics views of target VM**
- **SBCFI [Petroni, CCS 08] and HookSafe [Wang, CCS 09] check kernel data structures to detect and prevent rootkits**
- **SecVisor [Seshadri, SIGOPS 07] and Nickle [Riley, RAID 08] preserve kernel code integrity by preventing insertion of unauthenticated code in kernel space**
- **However, the aforementioned detection systems are designed to protect attacks on a single VM and are not suitable to protect VMs in the cloud.**

Kernel-Level RootKit Detection System in Cloud

- Problem Setting
  - User accesses service provided by cloud provider
  - Vulnerabilities exist in application service and/or host OS
  - Attacker may gain root privilege, install a kernel-level rootkit to launch stealth attack on VM
- Requirements of detection system
  - Light-weight / low overhead
  - Scalable
  - Easy to use

Kernel-level Rootkit Classification

Name	Hijack Tech	Insertion Tech
adore-ng	Dynamic: inode_ops	Module
enyelkm	Code: system_call	Module
kbeast	Static: sys_call_table	Module
knark	Static: sys_call_table	Module
mood-nt	Static: sys_call_table	/dev/kmem
override	Static: sys_call_table	Module
phantax	Static: sys_call_table	/dev/mem
suckit v2	Static: sys_call_table	/dev/mem

Kernel-level Rootkit Classification

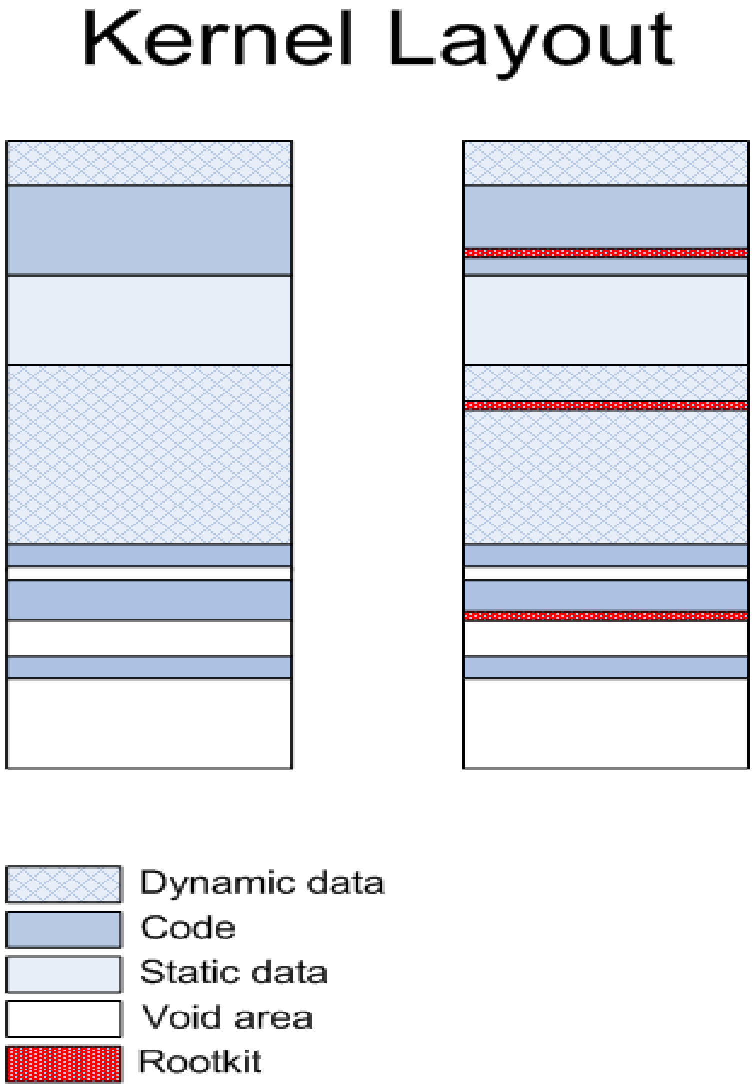
- Classification according to hijacking of control flow
  - Rootkits modifying kernel code
  - Rootkits modifying static data
    - Static data locates at the same address
    - Static data used by rootkits are usually read-only
  - Rootkits modifying dynamic data
    - Dynamic data used by rootkits are usually function pointers to kernel data structures
- Common characteristic
  - Code inserted into kernel space

Threat Model and Assumptions

- Threat model
  - External attacker installs rootkit in the OS kernel managing VMs by exploiting zero-day vulnerabilities in kernel and application software in VMs
  - Attacker gains control over multiple VMs to steal confidential data, modify memory, etc
- Assumptions
  - CPU supports NX-bit(Non-executable) feature, and Linux kernel utilizes this feature for memory protection
  - Kernel-level rootkits insert code into kernel space
  - VMM is not affected by rootkits

Design of RootkitDet

- **Rootkit Location**
  - Code of Kernel/Module
  - Dynamic allocated area
  - Unused space of Modules
- **Characteristics**
  - Related page entries are marked executable (NX-bit is cleared)



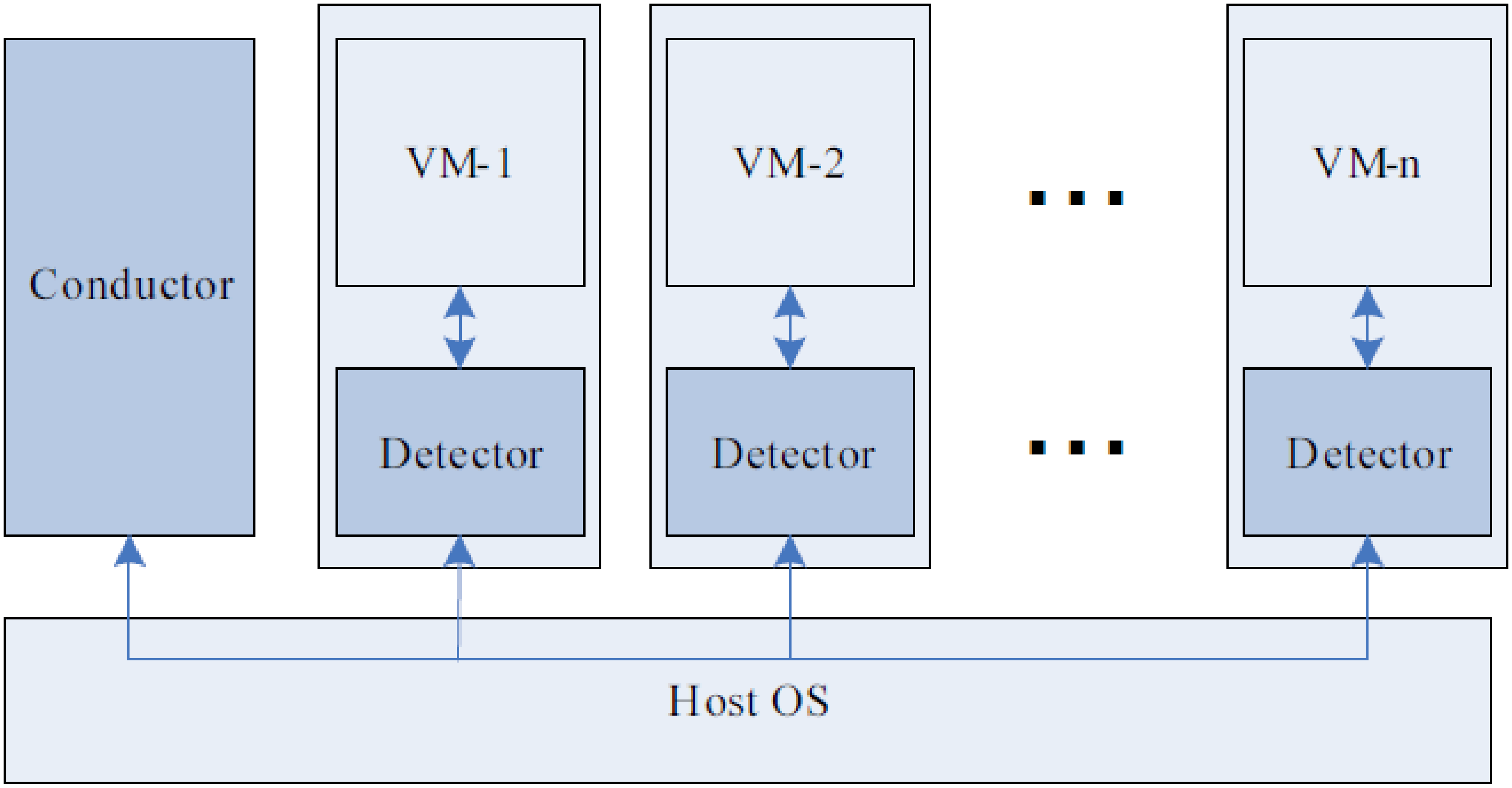
Design of RootkitDet

- Requirements
  - Extra executable regions in the kernel space
    - Read page directory entries of VM
  - Code in unused space of kernel modules
    - Read unused space of all kernel modules
  - Modifications of code of kernel and modules
    - Calculate hash values of code of kernel and modules
    - Original and current
- Challenges
  - Inconsistency of executable regions when kernel module is unloaded
    - Kernel frees unused virtual memory area in a lazy manner
  - Module's code is variable due to the relocation
    - Relocation address and symbols of itself
    - Symbols of main kernel, even other modules

Design of RootkitDet

- Overview of RootKitDet
  - Memory access of VMs
    - Take advantages of VMM, read memory of VM when it is suspended
  - Modification of Linux kernel
    - Free virtual memory areas after a module is unloaded
    - This won’t affect the efficiency of the kernel
  - Generation of original hash values of kernel and modules
    - Original filesystem image of VMs
    - Do relocation as what the kernel does to load a module

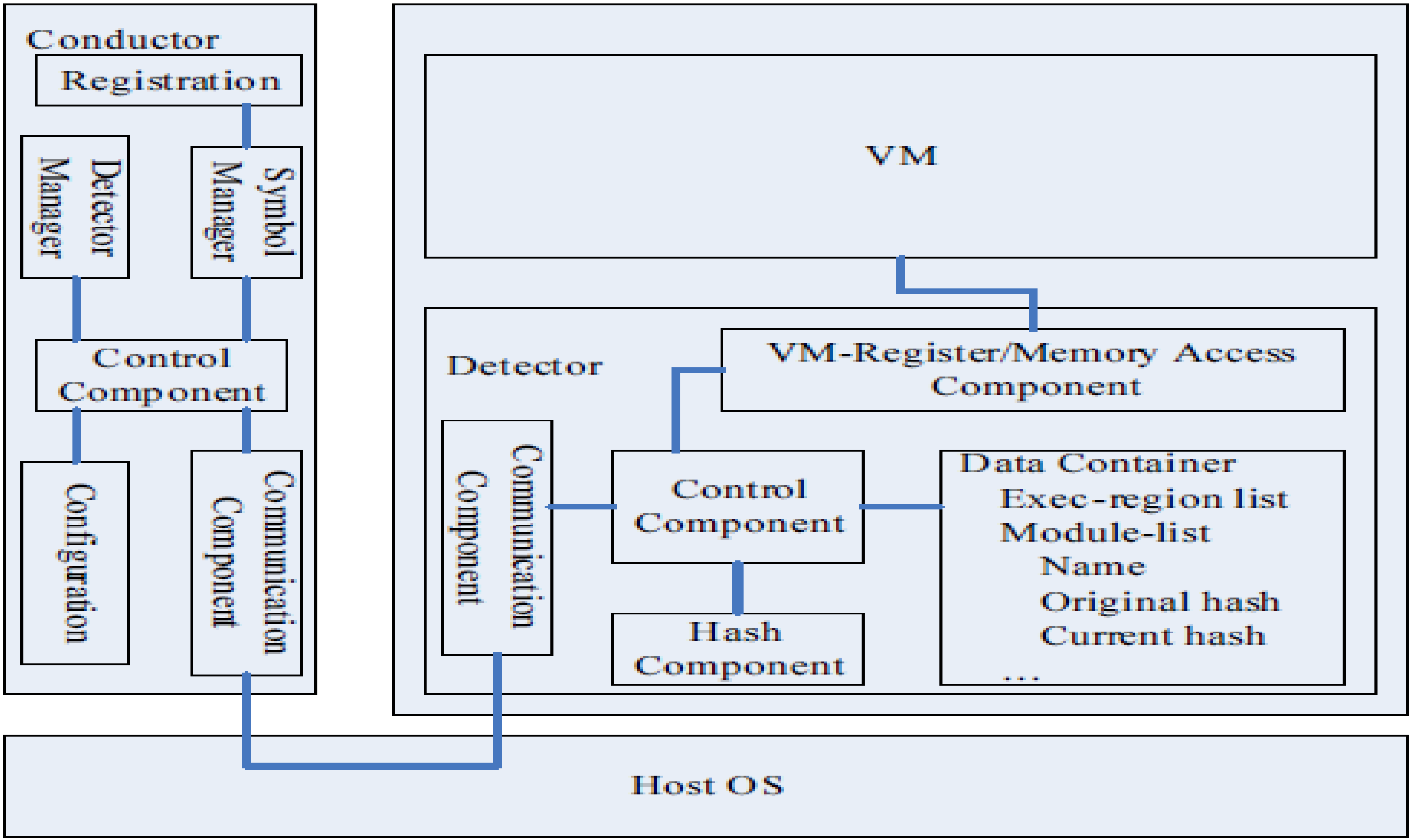
Design of RootkitDet



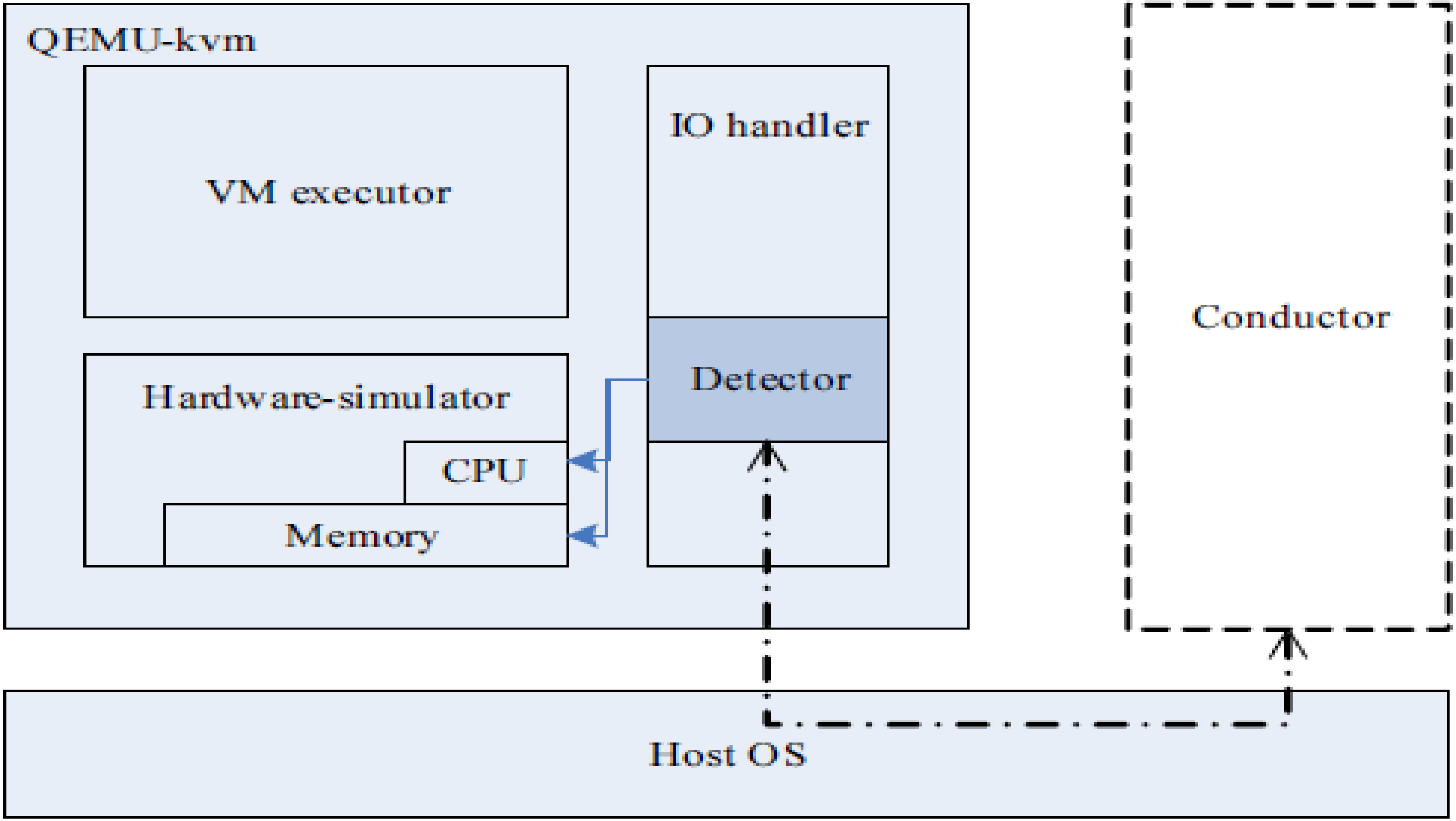
Design of RootkitDet

- Overview
  - Detector
    - Integrated into VMM
    - Detection of extra executable regions
    - Detection of code in unused space of kernel modules
    - Detection modification of code and kernel and modules
  - Conductor
    - User process independent of VMs
    - Communicate with Detector: get modules list, set original hash values
    - Calculate original hash values when necessary
    - Conduct the procedure of detection
    - Serve multiple Detectors

Design of RootkitDet

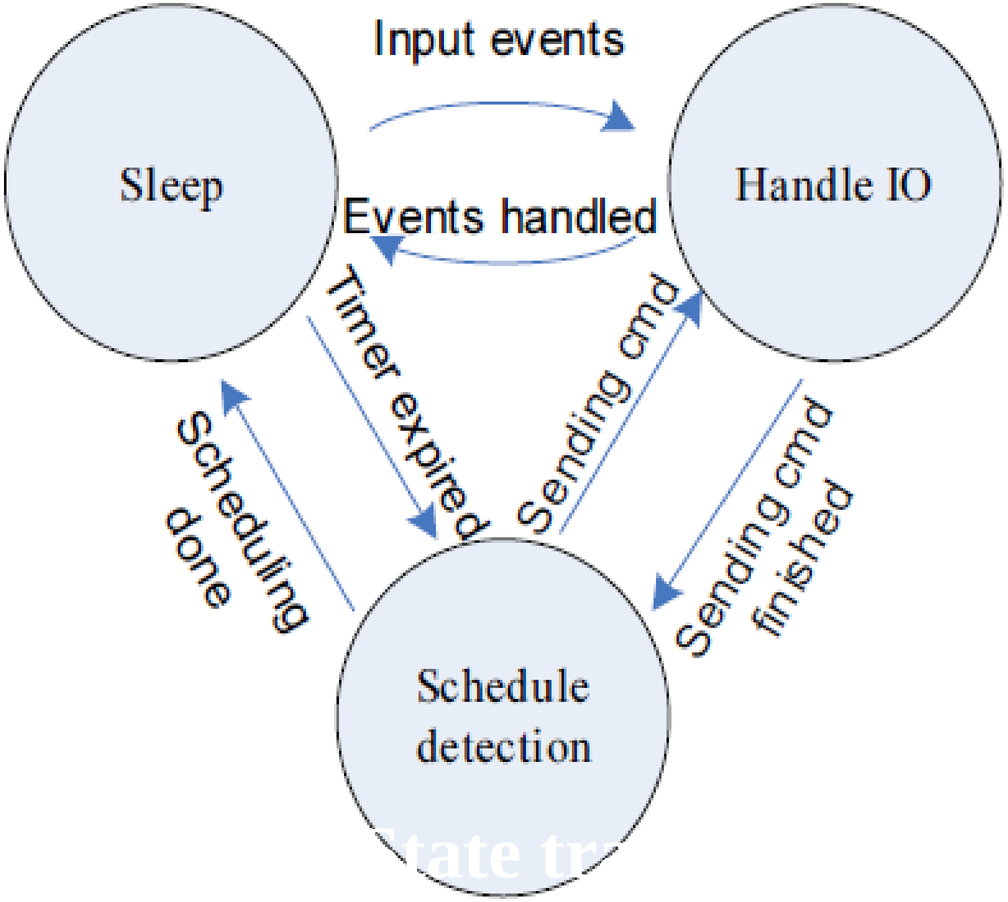


Implementation



Implementation

- **Conductor**
  - Schedule detector
  - Handle I/O
    - New connection
    - Response of detector
    - Configuration change
  - Sleep



Implementation

- **Detection procedures**
  1. **Detect extra executable regions**
  2. **Detect code in unused space of kernel modules**
  3. **Detect modifications to the code of kernel and modules**

Implementation

Algorithm 1: Detection Procedure 1

```
Data: No input data
Result: Rootkit_is_found

Rootkit_is_found = false;
list1 = get_executable_regions();
sort_by_address(list1);
list2 = get_kernel_and_modules();
sort_by_address(list2);
while list1 and list2 are both not empty do
    element1 = list1.top();
    element2 = list2.top();
    list1.remove_top();
    list2.remove_top();
    if element1 not match element2 then
        Rootkit_is_found = true;
        break;
    end
end
if list1 or list2 is not empty then
    Rootkit_is_found = true;
end
return Rootkit_is_found;
```

Implementation

Algorithm 2: Detection Procedure 2

Data: No input data
Result: Rootkit_is_found

```
Rootkit_is_found = false;
list = get_modules();
while list is not empty do
    element = list.top();
    list.remove_top();
    if unused_space_is_not_zero(element) then
        Rootkit_is_found = true;
        break;
    end
end
return Rootkit_is_found;
```

Algorithm 3: Detection Procedure 3

Data: No input data
Result: Rootkit_is_found

```
list = get_kernel_and_modules();
while list is not empty do
    element = list.top();
    list.remove_top();
    element.calculate_hash_value();
    if element.new_hash not match element.original_hash then
        Rootkit_is_found = true;
        break;
    end
end
return Rootkit_is_found;
```

Evaluation

- **Kernel-level rootkit detection**

Rootkit	Way to insert code	Detection Procedure
adore-ng	module	1
enyelkm	module and substitution	1/3
icmp-cmd	executable region	1
icmp-cmd_v2	unused space	2

- **Overhead of Detector**

Detection Procedure	Time consumed/us
1	189
2	713
3	47139

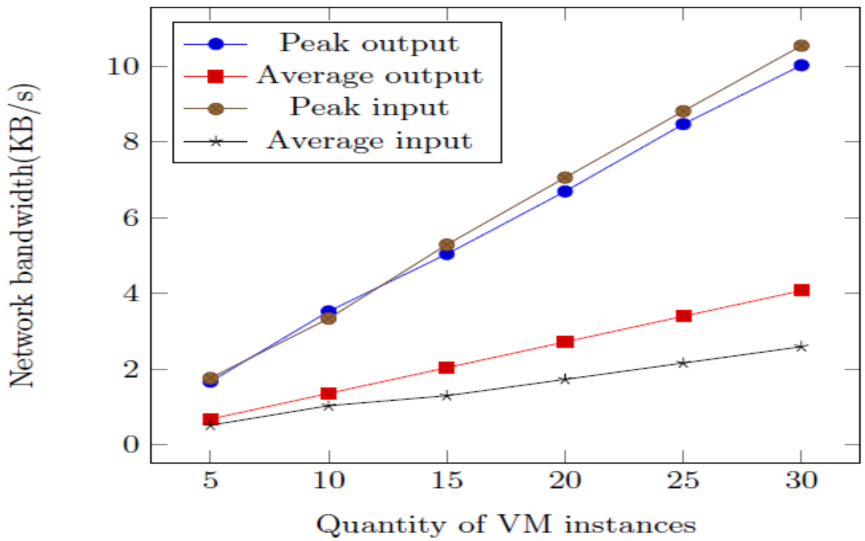
Evaluation

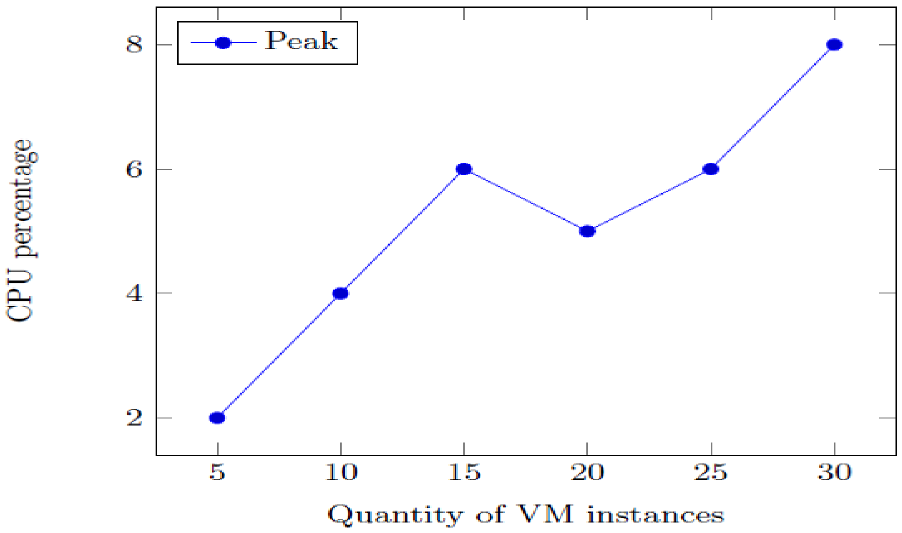
- **Overhead of Detector**
  - **Application benchmarks**

Benchmark	W/o Performance	W/i Performance	Relative Performance
Dhrystone	6040580.1 lps	6045164.7 lps	100.1%
Whetstone	630.6 MIPS	629.9 MIPS	99.9%
Lmbench(pipe bandwidth)	3843.2 MB/s	3810.3 MB/s	99.1%
Apache Bench(throughput)	569.95 KB/s	568.67 KB/s	99.8%
Kernel decompression	21.343 s	21.529 s	99.1%
Kernel build	1300.4 s	1292.9 s	100.1%

Evaluation

- **Conductor Performance**





Conclusion and Future Work

- Conclusion
  - Presented RootkitDet system, an efficient, scalable and easy to deploy kernel-level rootkit detection system in cloud
  - RootkitDet leverages the page directory of the kernel space in the guest OSes and the monitor functions provided by the VMM in the cloud detect rootkits
  - Experimental evaluation show that the RootkitDet system can effectively detect all of the kernel-level rootkits that insert code into kernel space with performance cost of less than 1%.
- Future Work
  - Migrate infected VM into QEMU after detection of “alien” code pages and detect control data or non-control data modifications

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Publications

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- Lingchen Zhang, Sachin Shetty, Peng Liu, Mohan Malkani, " A Scalable Kernel-Level Rootkit Detection System in the Cloud", in submission.

Thank You and Questions