AN MTD-BASED SELF-ADAPTIVE RESILIENCE APPROACH FOR CLOUD SYSTEMS

Miguel Villarreal-Vasquez¹, Bharat Bhargava¹, Pelin Angin², Noor Ahmed³, Daniel Goodwin⁴, Jason Kobes⁴, Kory Brin⁴

¹ Department of Computer Science, Purdue University
² Department of Computer Engineering, Middle East Technical University
³ Air Force Research Laboratory
⁴ Northrop Grumman Corporation

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MOTIVATION

Attack Surface
Replication approaches in cloud computing increase the attack surface. We need resilient/self-healing systems that can accurately detect anomalies and dynamically adapt themselves to keep performing mission-critical functions even under attacks and failures.
Is it possible to construct a generic attack-resilient framework for distributed cloud systems with a combination of dynamic network configuration and continuous replacement of virtual machines?
# Moving Target Defense (MTD)

## Attack Vectors
- Data
- Code
- Infrastructure
- Communications
- People

## Resilient Approaches
- Moving Target Defense (MTD)
- Proactive Restore/C2
- Least Privilege Enforcement
- Trust Zone Segmentation
- Identity Attribution
- Encryption
- Root Trust
The proposed Moving Target Defense (MTD) solution introduces resiliency and adaptability to the system through live monitoring, which transforms systems to be able to adapt and self-heal when ongoing attacks are detected.
Adversaries have an asymmetric advantage: They have the time to study a system, identify its vulnerabilities, and choose the time and place of attack to gain the maximum benefit.

The idea of moving-target defense (MTD): Imposing the same asymmetric disadvantage on attackers by making systems dynamic and therefore harder to explore and predict.

Threat Avoidance Techniques!
Fault-Tolerance Systems
- **Solution**: Replication/Redundancy:
- **Examples**: Quorum, Chain
- **Limitation**: Gives fault resiliency but increases attack surface at application level (common code base)

**DIVERSIFICATION/RANDOMIZATION**

Fault-Tolerance Systems
- **Solution**: MTD
- **Limitation**: Do not protect the entire host
The traditional defensive security strategy for distributed systems is to prevent attackers from gaining control of the system using well-established techniques: Replication/Redundancy, Encryption, etc.

- **Limitation:** Given sufficient time and resources, existing defensive methods can be defeated
• The state of the art of MTD solutions focus on randomization and diversification in particular layers of the system
  
  **Limitation:** Do not protect the entire host
PROPOSED APPROACH

• “Stay one-step ahead” of sophisticated attack
  • Protect the entire stack through dynamic interval-based spatial randomization
  • Avoid threats in-time intervals rather than defending the entire runtime of systems through Mobility and Direction
  • System will start secure, stay secure and return secure
  • Increase agility, anti-fragility and adaptability of the system
  • Unified generic MTD framework that enables reasoning about behavior of deployed systems on cloud platforms
OBJECTIVES OF THE MTD SOLUTION

• Aims to reduce the need to continuously fight against attacks by decreasing the gain-loss balance perception of attackers.

• Narrows the exposure window of a node to attacks, which increases the cost of attacks on a system and lowers the likelihood of success and the perceived benefit of compromising it.
OBJECTIVES OF THE MTD SOLUTION

• The **reduction in the vulnerability window of nodes** is mainly achieved **through three steps:**
  • Partitioning the runtime execution of nodes in time intervals
  • Allowing nodes to run only with a predefined lifespan (as low as a minute) on heterogeneous platforms (i.e. different OSs)
  • Proactively monitoring their runtime below the OS
**BENEFITS OF THE PROPOSED SOLUTION**

- **State of the Art System View:**

At a given time only **some** layers of the stack (Application, OS or Network) are checked/protected.
BENEFITS OF THE PROPOSED SOLUTION

- Proposed Solution System View:

At a given time **all** layers of the stack (Application, OS or Network) are checked/protected.
APPROACH OVERVIEW
MTD ARCHITECTURE

Components:
(1) Virtual Reincarnation (ViRA)  (3) SDN Network Dynamics
(2) Proactive Monitoring           (4) Systems States and Application Runtime
The MTD framework consists of the following four components:

- Virtual Machine Reincarnation (ViRA)
- Proactive Monitoring
- SDN Network Dynamics
- Systems States and Application Runtime

The framework will protect the whole stack; not only particular layers.
• Nodes run a distributed application on a given platform for a controlled period of time
• The running time is chosen in a way that successful ongoing attacks become ineffective
• The new fresh machine will integrate to the system and continue running the application after its data is updated
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The running time is chosen in a way that successful ongoing attacks become ineffective.

The new fresh machine will integrate to the system and continue running the application after its data is updated.
Randomization and diversification technique where nodes (virtual machines) running a distributed application vanish and reappear on a different virtual state with different guest OS, Host OS, hypervisor, and hardware.
How do we create replicas?

- Primary VM runs as no failures are detected.
- Alternate VM takes place when a failure occurs.
- Acceptance tests are adjusted independently to guarantee system operation.
- Alternate learn from Primary and become more robust to failures/attacks experimented by primary.

![Diagram showing the creation of replicas]
Challenges:

• Reduce downtime when Primary is replaced by Alternate and vice versa
• Keep the state of the machine (either Primary or Alternate) after the replacement to achieve uninterrupted operation
• Keeping the state (stateful reincarnation) allows the system to be application-agnostic
CREATION OF REPLICA

Stateful Reincarnation Ideas:

VM1

\[D, T\]

VM2

\[D', T'\]

VM3

\[D'', T''\]

VM4

\[D''', T'''\]

**Quorum**

D*: Synchronized Data

T*: Different version of Text

VM4 replaces VM1
Stateful Reincarnation Ideas:

- Create different versions of binaries
- The original code is kept and set with read-only permission so that it can be used as part of the reference to the new locations of the blocks in the re-randomized version.
- We avoid identifying and updating code position pointers in each randomization process by keeping a table of trampolines as shown in (b). Each block is located at a fixed offset (i.e., off_c) with respect to the trampoline table.
- The pointers (in the original code space) are dynamically redirected to its respective address in the code variant when it is de-referenced.

“Active machines are replaced by new ones with a totally new image”
PROACTIVE MONITORING

- Operates at the hypervisor level
- Helps for performing node reincarnation effectively rather than blindly
  - *Based on Virtual Machine Introspection (VMI)*
- Proactively gathers live memory data (at host OS) in intervals and reacts if anomalous behavior is detected
- Use libvmi library for introspection with negligible performance overhead
  - When application is hijacked, address offsets show new entries for injected code
  - When application is terminated and a new malicious one created, it could end up with a different process ID or memory address offset
• Network devices are reconfigured via OpenFlow on-the-fly
• New added flows redirect traffic intended for the old machine to the new machine
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OpenFlow Tables:
- table=0,priority=0,actions=…
- table=1,priority=0,actions=…
- table=2,ip,nw_dst=10.0.0.10,...
• New machines can be integrated to the system with their own IP addresses
• No waiting for the IP address of the old machine
• Downtime is reduced
A Byzantine fault tolerant (BFT-SMaRt) distributed application was run on a set of Ubuntu (either 12.04 or 14.04 randomly selected).

VMs run in a private cloud, and are connected with an SDN network using Open vSwitch.

The reincarnation is stateless, i.e. the new node (e.g. VM1') does not inherit the state of the replaced node (e.g. VM1).

The set of new VMs are periodically refreshed to start clean and the network is reconfigured using OpenFlow when a VM is reincarnated to provide continued access to the application.
MEASUREMENTS

1. **VM restart time**: Time it takes the machine to respond to be full operational since it is started.
2. **Virtual creation time**: Time to create the new image of the VM.
3. **Open vSwitch flow injection time**: Time it takes to inject new flows to Open vSwitch

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM restart time</td>
<td>~ 7s</td>
</tr>
<tr>
<td>VM creation time</td>
<td>~ 11s</td>
</tr>
<tr>
<td>Open vSwitch flow injection time</td>
<td>~ 250ms</td>
</tr>
</tbody>
</table>

**Note**: that the important factor for system downtime here is the Open vSwitch flow injection time, as VM creation and restart take place before the reincarnation process.
Aim to estimate the time it takes the new machine to be full operational.

VM creation and restart take place before the reincarnation process.

The important factor for system downtime here is the Open vSwitch flow injection time.
FUTURE WORK

• Enhanced live monitoring techniques
• Instrumentation to measure overhead more accurately
• Test other stateless applications on the MTD framework
  • E.g.: Upright (Public and Subscribe System)
• **Stateful Virtual Reincarnation Support:**
  - Can we preserve the state of the virtual machine during the reincarnation process to make the solution application-agnostic?
  - Test the framework with Secure SOA Services (stateful reincarnation)
PRESENTATION AND PUBLICATIONS

1. NGC Cyber Resilient Systems IRAD (http://www.northropgrumman.com)
2. Enterprise Resiliency IRAD (http://www.northropgrumman.com)