Pioneer: Verifying Code Integrity and Enforcing Untampered Code Execution on Legacy Systems[1]

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[1]Seshadri, A., Luk, M., Shi, E., Perrig, A., van Doorn, L., and Khosla, P. 2005. “Pioneer: verifying code integrity and enforcing untampered code execution on legacy systems”. In *Proceedings of the Twentieth ACM Symposium on Operating Systems Principles* (Brighton, United Kingdom, October 23 - 26, 2005). SOSP '05. ACM Press, New York, NY, 1-16.

Outline

- Verifiable code execution.
- TMP approach.
- Pioneer approach.
- Pioneer architecture.
- Adoption scenario: rootkit detector.

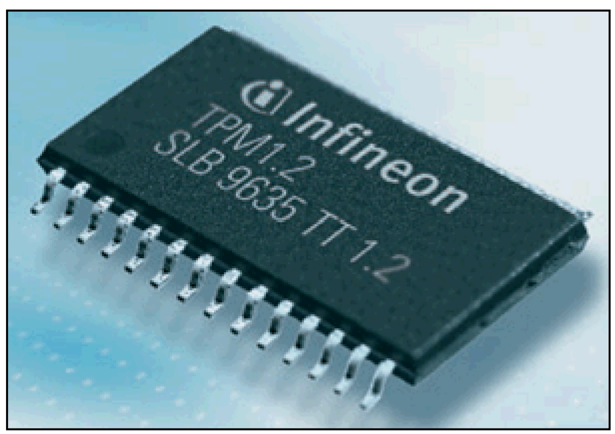
The problem

Verifiable code execution:

- Verifying that some arbitrary code is executed un-tampered on an un-trusted platform, even in the presence of malicious software on that platform.
  - The code is not modified before being invoked.
  - No alternate code is executed.
  - The execution state is not modified at run-time.

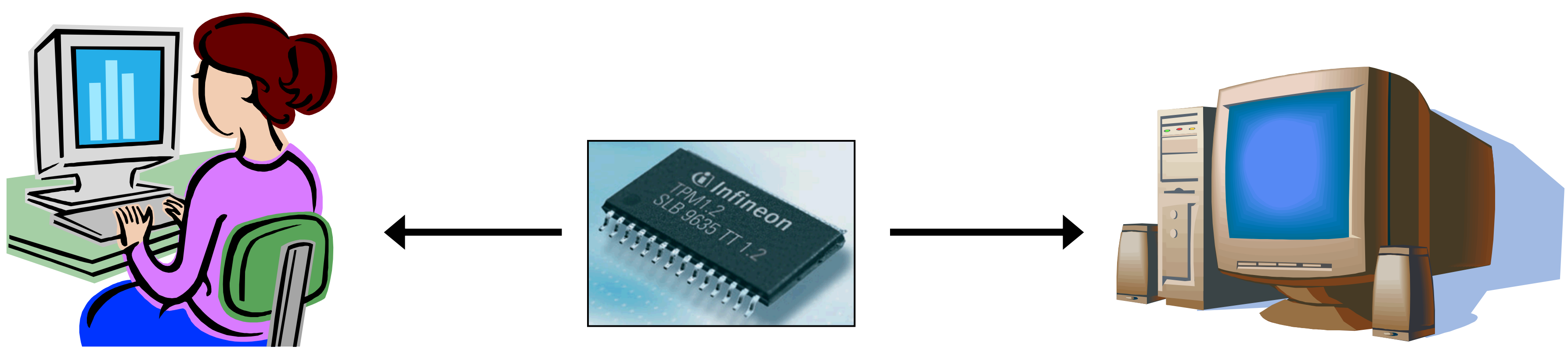
Trusted Platform Module

- TPM is a hardware security co-processor that provides some tamper resistant functions and secret keys.
- Secret keys generation.
- Cryptographic functions: encryption, decryption, hashing.
- Generation of ticks at a regular intervals (which can be signed by third party authorities)
- Monotonic counter function



Remote attestation

- TMP is used to measure the state of the platform during the boot process.
- Malicious code is detected because it causes measurements to deviate from the expected values.
- Measurements are stored in the Platform Configuration Registers (PCR) within TMP.
- Remote attestation allows a party to obtain assurance in the correct operation of a remote system.



Trusted Platform Module

- TMP based authentication can not be applied on legacy systems (where no special purpose hardware is available).
- Collision resistance property of SHA-1 hashing function has been compromised.
  - Tampered code with the same signature as the authentic one.
- When a fault is revealed it is not possible to fix it without replacing all the hardware.

Pioneer

- Software based primitive to verify code execution on an un-trusted legacy host
  - It can be updated.
  - No special purpose hardware is required.
  - No particular CPU extension (*e.g.,* virtualization).
  - It provides run-time attestation.
- It is based on
  - Challenge-response protocol.
  - External trusted entity.
  - Communication link.

Assumptions

Dispatcher:

- It knows the exact hardware configuration of the un-trusted client.

Un-trusted client:

- Single CPU (not over-clocked).
- CPU does not support Symmetric Multi-Threading.

Communication channel:

- Message origin authentication.
- Un-trusted platform can only communicate with the dispatcher when Pioneer runs.

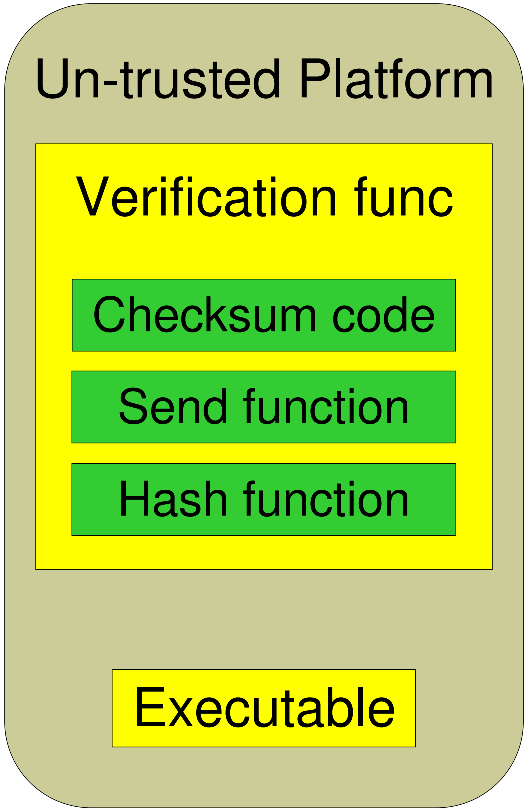
Attacker model

- The attacker has complete control of the software on the un-trusted platform (administrator privileges)
  - Applications.
  - Operative system.
- The attacker can not modify the hardware
  - He can not load malicious firmware on disk controllers or network interfaces.
  - He can not replace the CPU with a faster one.
  - He can not perform DMA-attacks.

Verification function

- The verification function checks itself.
- It performs the integrity measurements on the executables.

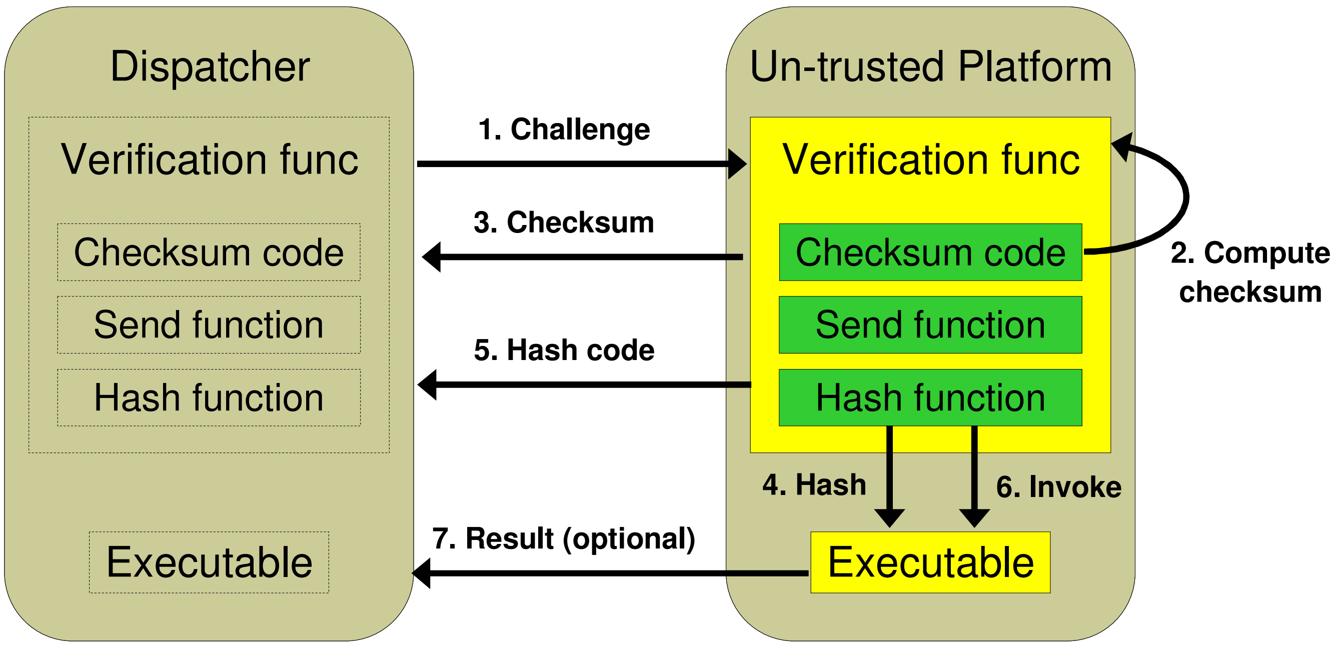
- Checksum code
  - It sets up the un-tampered environment.
  - It computes a fingerprint of the whole verification function.
  - Any attack will result in a noticeable time increase.
- Hash function
  - It depends on the challenge sent by the dispatcher.



The challenge-response protocol

- The dispatcher obtains the assurance that dynamic root of trust exists on the un-trusted platform.
- The dispatcher uses the dynamic root of trust to guarantee the verifiable code execution.

1.	$D:$	$t_1 \leftarrow$ current time, $nonce \xleftarrow{R} \{0,1\}^n$
	$D \rightarrow P:$	$\langle nonce \rangle$
2.	$P:$	$c \leftarrow \text{Checksum}(nonce, P)$
3.	$P \rightarrow D:$	$\langle c \rangle$
	$D:$	$t_2 \leftarrow$ current time if $(t_2 - t_1 > \Delta t)$ then exit with failure else verify checksum c
4.	$P:$	$h \leftarrow \text{Hash}(nonce, E)$
5.	$P \rightarrow D:$	$\langle h \rangle$
	$D:$	verify measurement result h
6.	$P:$	transfer control to E
7.	$E \rightarrow D:$	$\langle$result (optional)$\rangle$



Time-optimal implementation of checksum function

- A tampered checksum computation results in time overhead.
- The adversary could use saved time to forge the checksum.
- Function implemented as sequence of XOR and AND.
  - Difficult to parallelize.
  - Strongly ordered.
  - Multiple instructions are issued in a superscalar processor.
  - No other issue slot are available for malicious code.

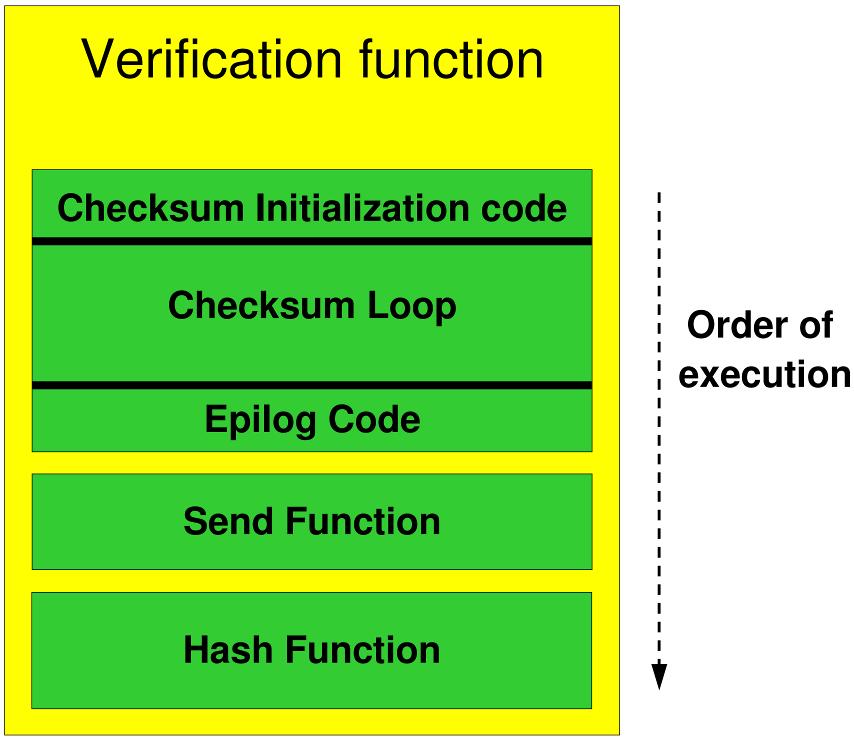
a_1
a_2
a_3
a_4
…

$$checksum = [(a_1 \oplus a_2) + a_3] \oplus a_4$$

$$\neq (a_1 \oplus a_2) + (a_3 \oplus a_4)$$

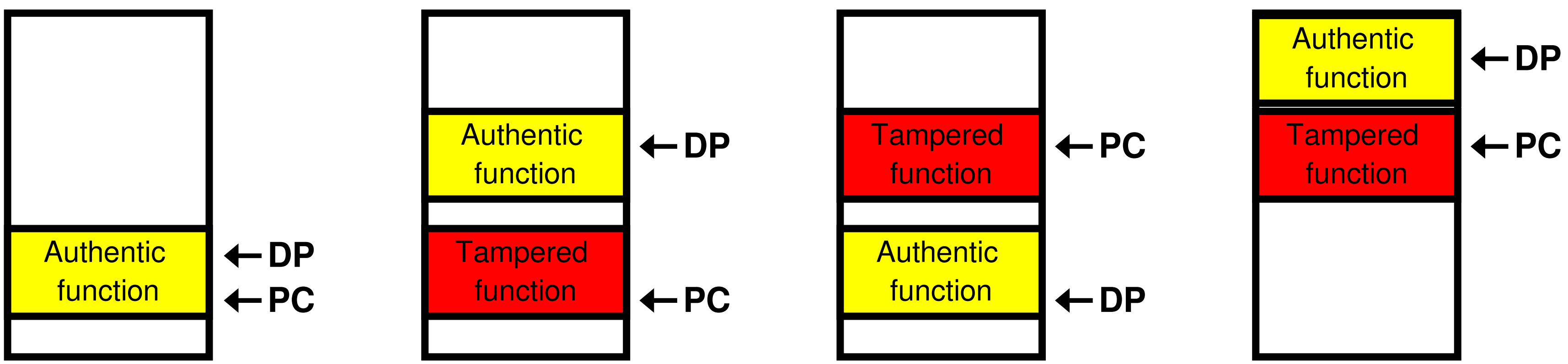
Iterative checksum code

- Adversary who manipulates the input in every iteration of the checking function causes a constant time overhead per iteration.



Checksum includes CPU state

- The adversary compute the checksum on a correct copy of the tampered verification function (Memory copy attack).
- Incorporate both PC and DP into the checksum computation, so when they are required the adversary loses time to forge them.

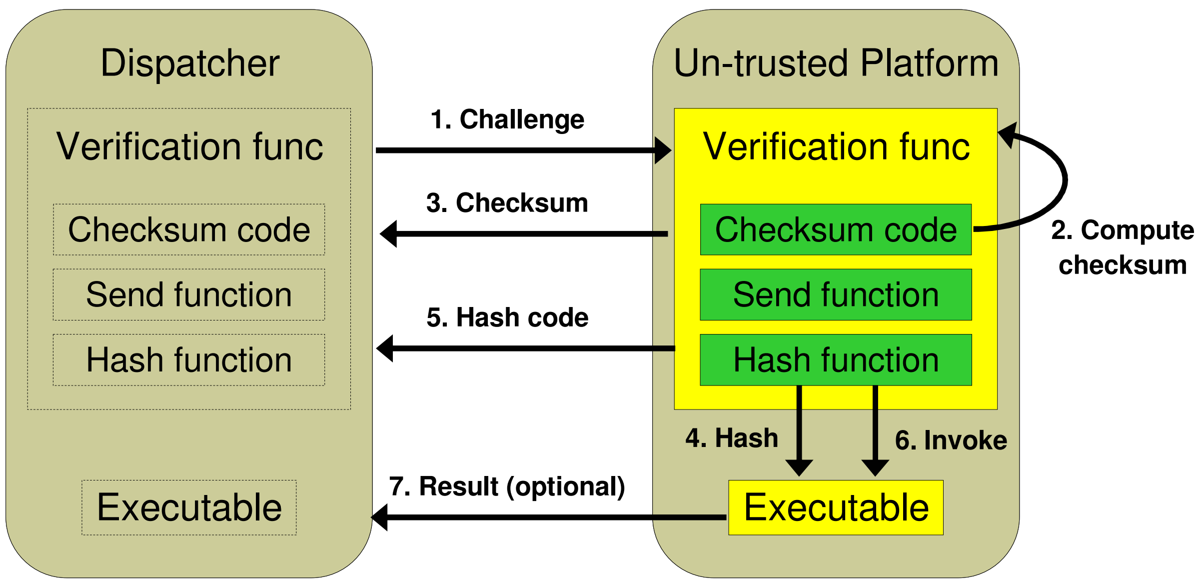


Low variance in execution time

- Checking code is small enough to fit into L1 CPU instruction cache.
- Verification function is small enough to fit into L1 CPU data cache.
- Checksum code execute at the highest privilege level.
- All the maskable interrupts are turned off.
- Reduced number of non-issuable instruction (no out-of order execution in superscalar processors).
- No external function (os, library) is called.

Dispatcher challenge

- The checksum depends on the challenge sent by the dispatcher.
  - The adversary can not pre-compute the checksum.
  - Challenge is used to initialize a pseudo-random number generator used in pseudo-random memory traversal.
  - Challenge is the initialization value for the checksum.



Execution environment

- Turn off all the maskable interrupts
  - Success only if running at the highest privilege level.
  - Failure in case of lower privilege.
  - Time overhead if running in a software virtual machine monitor (*e.g.,* VMware).
- Register flags are incorporated in each checksum iteration.
- Exception handler for all non-maskable interrupts is replaced with the “interrupt-return” instruction.
- Call stack is used to store part of the checksum during its computation.

How many iterations?

- Adversary can pre-load verification function into L1 CPU cache (no cache miss) and have a zero RTT
  - Adversary time advantage (a).
- Adversary overhead per iteration (o) .
  - Total overhead increases linearly with the number of iterations (n*o/c).
- CPU clock speed (c).

$$\boxed{n > \frac{c * a}{o}}$$

Experimental results

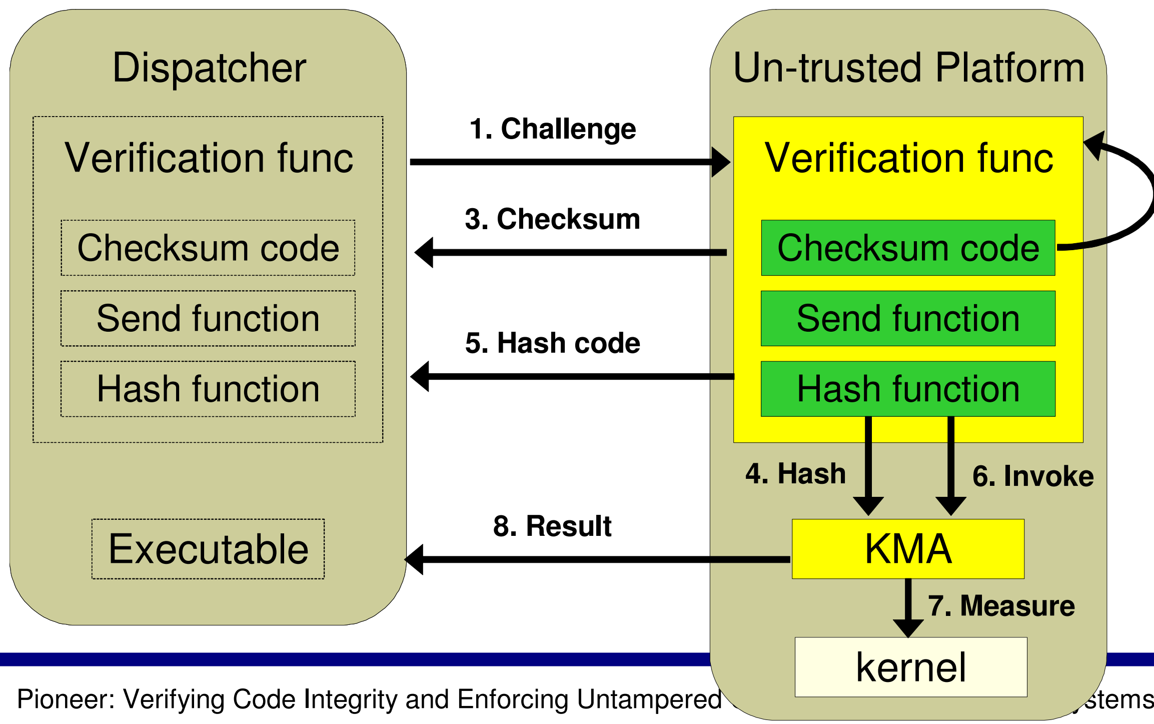
- RTT is evaluated considering the PING latency on different host in the LAN segment.
  - RTT < 0.25 ms
- Cache pre-warming time evaluated empirically
  - 0.0016 ms
- a = 0.2516 ms
- o = 0.6 CPU cycle per iteration
- n = 1,250,000 iterations (on 2.8Ghz CPU)
- To prevent false positives n is doubled (2,500,000 iterations).
- r = time to perform 2,500,000 iterations
- If dispatcher receive the answer after r + RTT it is considered in late.

Rootkits

- Rootkit is a software installed by an intruder on a host that allows the intruder to gain privileged access to the host, while remaining undetected.
  - Some rootkits do not modify the kernel (easy to locate).
  - Some rootkits do modify the kernel (kernel can not be trusted to locate them).

Kernel rootkit detector

- Pioneer is used to guarantee the verifiable code execution of the Kernel Measurement Agent (KMA).
- KMA is used to compute the hash value of the running kernel.
- KMA runs at kernel privilege.
  - Kernel is hashed.
  - Module pointer is checked.
  - Kernel version is checked.
  - Return address is checked.



Experimental results

- Rootkit detector runs every 5 seconds.
- Computational and I/O intensive operations are used as benchmarks.
  - PostMark: file system benchmark.
  - Bunzip2: uncompress all the firefox source code.
  - Copy: copy of all the Linux source code (1.33 Gb).

Benchmark	Standalone	Rootkit detector	Overhead
PostMark	52	52.99	1.9%
Bunzip2	21.296	21.713	1.5%
Copy	373	385	3.2%

Open issues

- Formal proof of code optimality.
- Avoid that an adversary can use mathematical methods to generate a function that computes the same checksum when fed with the same input.
- Provide a checksum function which is CPU independent.
- Increase the time overhead for an attack.

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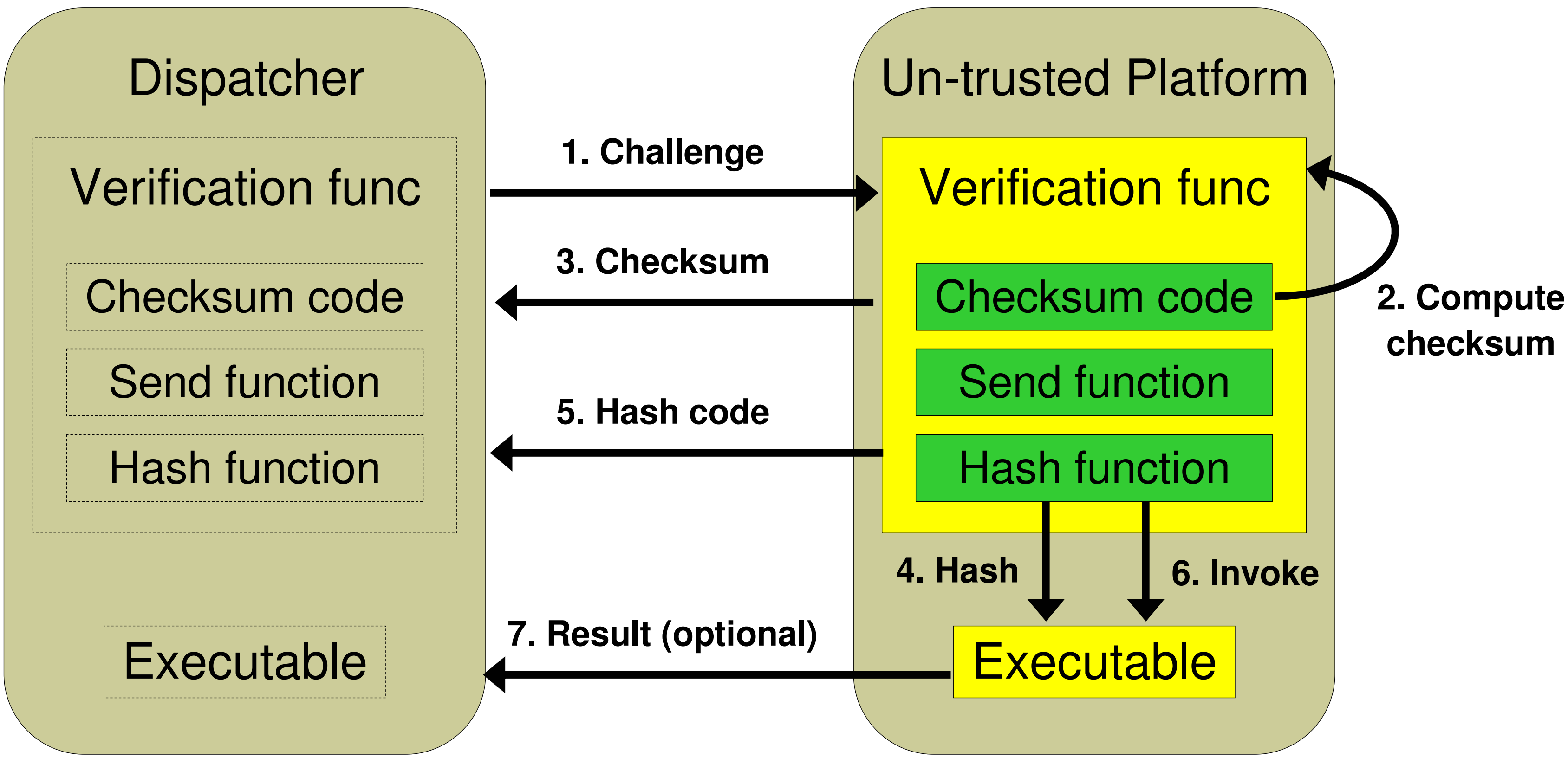
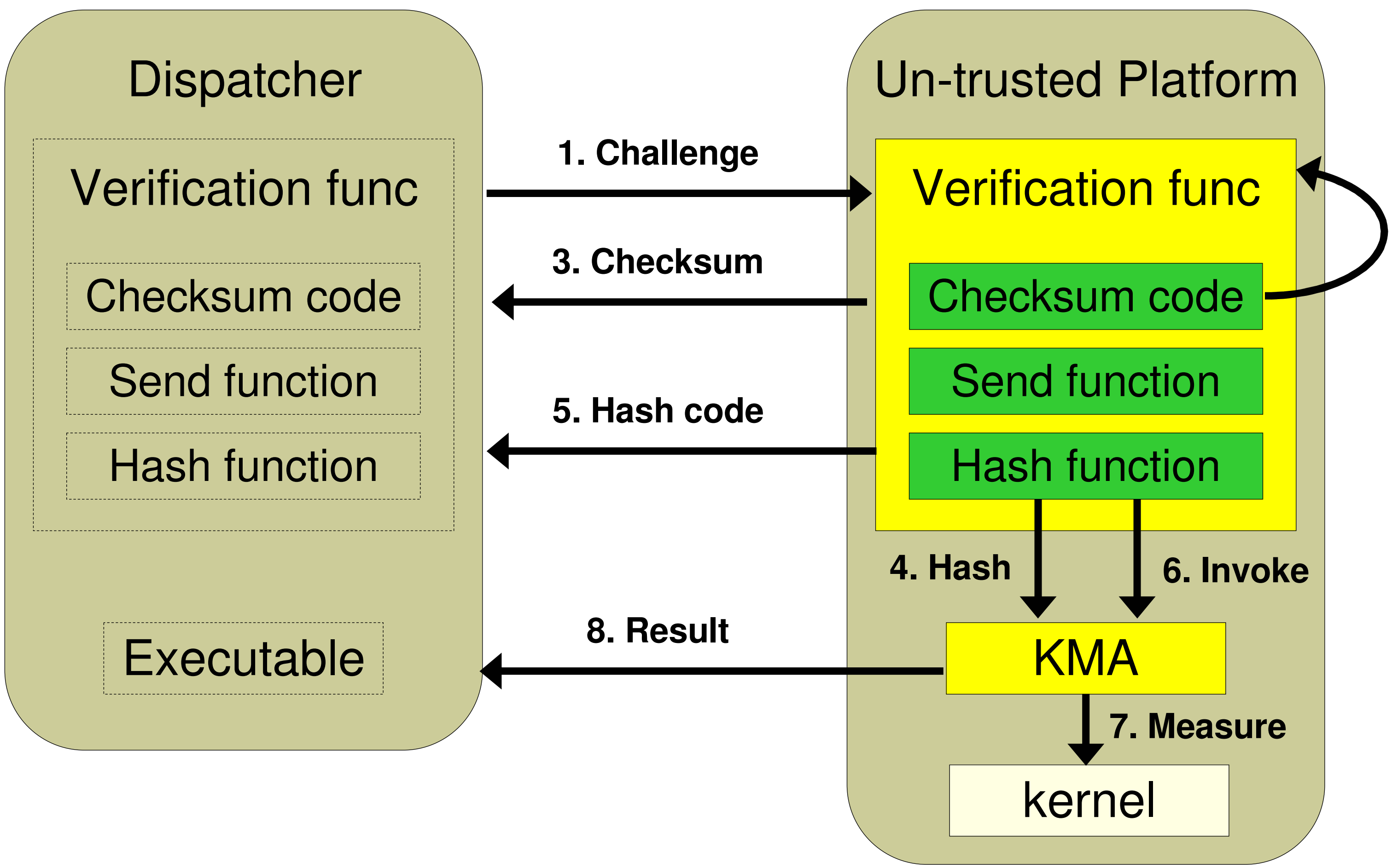
Pioneer architecture





Dispatcher
Verification func
Checksum code
Send function
Hash function
Executable
1. Challenge
3. Checksum
5. Hash code
8. Result
Un-trusted Platform
Verification func
Checksum code
Send function
Hash function
4. Hash
6. Invoke
KMA
7. Measure
kernel