WELES: Policy-driven Runtime Integrity Enforcement of Virtual Machines

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Abstract

Trust is of paramount concern for tenants to deploy their security-sensitive services in the cloud. The integrity of virtual machines (VMs) in which these services are deployed needs to be ensured even in the presence of powerful adversaries with administrative access to the cloud. Traditional approaches for solving this challenge leverage trusted computing techniques, e.g., vTPM, or hardware CPU extensions, e.g., AMD SEV. But, they are vulnerable to powerful adversaries, or they provide only load time (not runtime) integrity measurements of VMs.

We propose WELES, a protocol allowing tenants to establish and maintain trust in VM runtime integrity of software and its configuration. WELES is transparent to the VM configuration and setup. It performs an implicit attestation of VMs during a secure login and binds the VM integrity state with the secure connection. Our prototype’s evaluation shows that WELES is practical and incurs low performance overhead (≤ 6%).

1 Introduction

Cloud computing paradigm shifts the responsibility of the computing resources management from application owners to cloud providers, allowing application owners (tenants) to focus on their business use cases instead of on hardware management and administration. However, trust is of paramount concern for tenants operating security-sensitive systems because software managing computing resources and its configuration and administration remains out of their control. Tenants have to trust that the cloud provider, its employees, and the infrastructure protect the tenant’s intellectual property as well as the confidentiality and the integrity of the tenant’s data. A malicious employee [8], or an adversary who gets into possession of employee credentials [74, 50], might leverage administrator privileges to read the confidential data by introspecting virtual machine (VM) memory [85], to tamper with computation by subverting the hypervisor [54], or to redirect the tenant to an arbitrary VM under her control by altering a network configuration [91]. We tackle the problem of how to establish trust in a VM executed in the cloud. Specifically, we focus on the integrity of legacy systems executed in a VM.

The existing attestation protocols focus on leveraging trusted hardware to report measurements of the execution environment. In trusted computing [34], the trusted platform module attestation [11] and integrity measurement architecture (IMA) [78] provide a means to enforce and monitor integrity of the software that has been executed since the platform bootstrap [7]. The virtual TPM (vTPM) [19] design extends this concept by introducing a software-based trusted platform module (TPM) that, together with the hardware TPM, provides integrity measurements of the entire software stack — from the firmware, the hypervisor, up to the VM. However, this technique cannot be applied to the cloud because an adversary can tamper with the communication between the vTPM and the VM. For example, by reconfiguring the network, she can mount a man-in-the-middle attack to perform a TPM reset attack [53], compromising the vTPM security guarantees.

A complementary technology to trusted computing,
trusted execution environment (TEE)\cite{46}, uses hardware extensions to exclude the administrator and privileged software, i.e., operating system, hypervisor, from the trusted computing base. The Intel software guard extensions (SGX)\cite{29} comes with an attestation protocol that permits remotely verifying application’s integrity and the genuineness of the underlying hardware. However, it is available only to applications executing inside an SGX enclave. Legacy applications executed inside an enclave suffer from performance limitations due to a small amount of protected memory\cite{15}. The SGX adoption in the virtualized environment is further limited because the protected memory is shared among all tenants.

Alternative technologies isolating VMs from the untrusted hypervisor, e.g., AMD SEV\cite{52,51} or IBM PEF\cite{44}, do not have memory limitations. They support running the entire operating system in isolation from the hypervisor while incurring minimal performance overhead\cite{41}. However, their attestation protocol only provides information about the VM integrity at the VM initialization time. It is not sufficient because the loaded operating system might get compromised later—at runtime— with operating system vulnerabilities or misconfiguration\cite{88}. Thus, to verify the runtime (post-initialization) integrity of the guest operating system, one would still need to rely on the vTPM design. But, as already mentioned, it is not enough in the cloud environment.

Importantly, security models of these hardware technologies isolating VM from the hypervisor assume threats caused by running tenants’ OSes in a shared execution environment, i.e., attacks performed by rogue operators, compromised hypervisor, or malicious co-tenants. These technologies do not address the fact that a typical tenant’s OS is a complex mixture of software and configuration with a large vector attack. I.e., the protected application is not, like in the SGX, a single process, but the kernel, userspace services, and applications, which might be compromised while running inside the TEE and thus exposes tenant’s computation and data to threats. These technologies assume it is the tenant’s responsibility to protect the OS, but they lack primitives to enable runtime integrity verification and enforcement of guest OSes. This work proposes means to enable such primitives, which are neither provided by the technologies mentioned above nor by the existing cloud offerings.

We present WELES, a VM remote attestation protocol that provides integrity guarantees to legacy systems executed in the cloud. WELES has noteworthy advantages. First, it supports legacy systems with zero-code changes by running them inside VMs on the integrity-enforced execution environment. To do so, it leverages trusted computing to enforce and attest to the hypervisor’s and VM’s integrity. Second, WELES limits the system administrator activities in the host OS using integrity-enforcement mechanisms, while relying on the TEE to protect its own integrity from tampering. Third, it supports tenants connecting from machines not equipped with trusted hardware. Specifically, WELES integrates with the secure shell (SSH) protocol\cite{89}. Login to the VM implicitly performs an attestation of the VM.

Our contributions are as follows:
• We designed a protocol, WELES, attesting to the VM’s runtime integrity\cite{34}.
• We implemented the WELES prototype using state-of-the-art technologies commonly used in the cloud\cite{55}.
• We evaluated it on real-world applications\cite{45}.

2 Threat model

We require that the cloud node is built from the software which source code is certified by a trusted third party\cite{3} or can be reviewed by tenants, e.g., open-source software\cite{13} or proprietary software accessible under non-disclosure agreement. Specifically, such software is typically considered safe and trusted when (i) it originates from trusted places like the official Linux git repository; (ii) it passes security analysis like fuzzing\cite{90}; (iii) it is implemented using memory safe languages, like Rust; (iv) it has been formally proven, like seL4\cite{55} or EverCrypt\cite{72}; (v) it was compiled with memory corruption mitigations, e.g., position-independent executables with stack-smashing protection.

Our goal is to provide tenants with an runtime integrity attestation protocol that ensures that the cloud node (i.e., host OS, hypervisor) and the VM (guest OS, tenant’s legacy application) run only expected software in the expected configuration. We distinguish between an internal and an external adversary, both without capabilities of mounting physical and hardware attacks (e.g.,\cite{87}). This is a reasonable assumption since cloud providers control and limit physical access to their data centers.
An internal adversary, such as a malicious administrator or an adversary who successfully extracted administrators’ credentials, aims to tamper with a hypervisor configuration or with a VM deployment to compromise the integrity of the tenant’s legacy application. She has remote administrative access to the host machine that allows her to configure, install, and execute software. The internal adversary controls the network that will allow her to insert, alter, and drop network packages.

An external adversary resides outside the cloud. Her goal is to compromise the security-sensitive application’s integrity. She can exploit a guest OS misconfiguration or use social engineering to connect to the tenant’s VM remotely. Then, she runs dedicated software, e.g., software debugger or custom kernel, to modify the legacy application’s behavior.

We consider the TPM, the CPU, and their hardware features trusted. We rely on the soundness of cryptographic primitives used by software and hardware components. We treat software-based side-channel attacks (e.g., [58]) as orthogonal to this work because of (i) the countermeasures existence (e.g., [67]) whose presence is verifiable as part of the WELES protocol, (ii) the possibility of provisioning a dedicated (not shared) machine in the cloud.

3 Background and Problem Statement

Load-time integrity enforcement. A cloud node is a computer where multiple tenants run their VMs in parallel on top of the same computing resources. VMs are managed by a hypervisor, a privileged layer of software providing access to physical resources and isolating VMs from each other. Since the VM’s security depends on the hypervisor, it is essential to ensure that the correct hypervisor controls the VM.

The trusted computing [34] provides hardware and software technologies to verify the hypervisor’s integrity. In particular, the dynamic root of trust for measurements (DRTM) [81] is a mechanism available in modern CPUs that establishes a trusted environment in which a hypervisor is securely measured and loaded. The hypervisor’s integrity measurements are stored inside the hardware TPM chip in dedicated memory regions called platform configuration registers (PCRs) [11]. PCRs are tamper-resistant. They cannot be written directly but only extended with a new value using a cryptographic hash function: $\text{PCR}_{\text{extend}} = \text{hash}(\text{PCR}_{\text{old}} \parallel \text{data}_{\text{to extend}})$.

The TPM attestation protocol [40] defines how to read a report certifying the PCRs values. The report is signed using a cryptographic key derived from the endorsement key, which is an asymmetric key embedded in the TPM chip at the manufacturing time. The TPM also stores a certificate, signed by a manufacturer, containing the endorsement key’s public part. Consequently, it is possible to check that a genuine TPM chip produced the report because the report’s signature is verifiable using the public key read from the certificate.

Runtime integrity enforcement. The administrator has privileged access to the machine with complete control over the network configuration, with permissions to install, start, and stop applications. These privileges permit him to trick the DRTM attestation process because the hypervisor’s integrity is measured just once when the hypervisor is loaded to the memory. The TPM report certifies this state until the next DRTM launch, i.e., the next computer boot. Hence, after the hypervisor has been measured, an adversary can compromise it by installing an arbitrary hypervisor [75] or downgrading it to a vulnerable version without being detected.

Integrity measurement architecture (IMA) [7, 78, 43] allows for mitigation of the threat mentioned above. Being part of the measured kernel, IMA implements an integrity-enforcement mechanism [43], allowing for loading only digitally signed software and configuration. Consequently, signing only software required to manage VMs allows for limiting activities carried out by an administrator on the host machine. A load of a legitimate kernel with enabled IMA and input-output memory management unit is ensured by DRTM, and it is attestable via the TPM attestation protocol.

Integrity auditing. IMA provides information on what software has been installed or launched since the kernel loading, what is the system configuration, and whether the system configuration has changed. IMA provides a tamper-proof history of collected measurements in a dedicated file called IMA log. The tamper-proof property is maintained because IMA extends to the PCR the measurements of every executable, configuration file, script, and
Although the TLS helps protect the communication’s integrity, lack of authentication between the vTPM and the hypervisor still enables an adversary to fully control the communication by placing a proxy in front of the vTPM. In more detail, an adversary can configure the hypervisor in a way it communicates with vTPM via an intermediary software, which intercepts the communication (Figure 1b). She can then drop arbitrary measurements or perform the TPM reset attack [53], thus compromising the vTPM security guarantees.

To mitigate the attack, the vTPM must ensure the remote peer’s integrity (is it the correct hypervisor?) and its locality (is the hypervisor running on the same platform?). Although the TEE local attestation gives information about software integrity and locality, we cannot use it here because the hypervisor cannot run inside the TEE. However, suppose we find a way to satisfy the locality condition. In that case, we can leverage integrity measurements (IMA) to verify the hypervisor’s integrity because among trusted software running on the platform there can be only one that connects to the vTPM—the hypervisor. To satisfy the locality condition, we make the following observation: Only software running on the same platform has direct access to the same hardware TPM. We propose to share a secret between the vTPM and the hypervisor using the hardware TPM (§4.4). The vTPM then authenticates the hypervisor by verifying that the hypervisor presents the secret in the pre-shared key TLS authentication.

Finally, an adversary who compromises the guest OS can mount the cuckoo attack [69] to impersonate the legitimate VM. In more detail, an adversary can modify the TPM driver inside a guest OS to redirect the TPM communication to a remote TPM (Figure 1c). A verifier running inside a compromised VM cannot recognize if he communicates with the vTPM attached to his VM or with a remote vTPM attached to another VM. The verifier is helpless because he cannot establish a secure channel to the vTPM that would guarantee communication with the local vTPM. To mitigate the attack, we propose leveraging the TEE attestation protocol to establish a secure communication channel between the verifier and the vTPM and to use it to exchange a secret allowing the verifier to identify the vTPM instance uniquely (§4.5).

Problems with virtualized TPMs. The TPM chip cannot be effectively shared with many VMs due to a limited amount of PCRs. The vTPM [19] design addresses this problem by running multiple software-based TPMs exposed to VMs by the hypervisor. This design requires verifying the hypervisor’s integrity before establishing trust with a software-based TPM. We argue that verifying the hypervisor’s integrity alone is not enough because an administrator can break the software-based TPM security guarantees by mounting a man-in-the-middle (MitM) attack using the legitimate software, as we describe next. Consequently, the vTPM cannot be used directly to provide runtime integrity of VMs.

In the vTPM design, the hypervisor prepends a 4-byte vTPM identifier that allows routing the communication to the correct vTPM instance. However, the link between the vTPM and the VM is unprotected [31], and it is routed through an untrusted network. Consequently, an adversary can mount a masquerading attack to redirect the VM communication to an arbitrary vTPM (Figure 1a) by replacing the vTPM identifier inside the network package. To mitigate the attack, we propose to use the transport layer security (TLS) protocol [9] to protect the communication’s integrity.

Dynamic library before such file or program is read or executed. Consequently, an adversary who tampers with the IMA log cannot hide her malicious behavior because she cannot modify the PCR value. She cannot overwrite the PCR and she cannot reset it to the initial value without rebooting the platform.

Figure 1: An adversary with root access to the hypervisor can violate the security guarantees promised by the vTPM [19] design.
4 WELES design

Our objective is to provide an architecture that: 1. protects legacy applications running inside a VM from threats defined in §2. 2. requires zero-code changes to legacy applications and the VM setup, 3. permits tenants to remotely attest to the platform runtime integrity without possessing any vendor-specific hardware.

4.1 High-level Overview

Figure 2 shows an overview of the cloud node running WELES. It consists of the following four components: (A) the VM, (B) the hypervisor managing the VM, providing it with access to physical resources and isolating from other VMs, (C) trusted computing components enabling hypervisor’s runtime integrity enforcement and attestation, (D) WELES, software executed inside TEE that allows tenants to attest and enforce the VMs’ integrity.

The configuration, the execution, and the operation of the above components are subject to attestation. First, the cloud operator bootstraps the cloud node and starts WELES. At the tenant’s request, the cloud provider spawns a VM (➀). Next, the tenant establishes trust with WELES (➁), which becomes the first trusted component on a remote platform. The tenant requests WELES to check if the hypervisor conforms to the policy (➂), which contains tenant-specific trust constraints, such as integrity measurements (➃). WELES uses IMA and TPM to verify that the platform’s runtime integrity conforms to the policy and then generates a VM’s public/private key pair. The public key is returned to the tenant (➃). WELES protects access to the private key, i.e., it permits the VM to use the private key only if the platform matches the state defined inside the policy. Finally, the tenant establishes trust with the VM during the SSH-handshake. He verifies that the VM can use the private key corresponding to the previously obtained public key (➄). The tenant authenticates himself in a standard way, using his own SSH private key. His SSH public key is embedded inside the VM’s image or provisioned during the VM deployment.

4.2 Tenant Isolation and Security Policy

Multiple applications with different security requirements might coexist on the same physical machine. WELES allows ensuring that applications run in isolation from each other and match their security requirements. Figure 3 shows how WELES assigns each VM a pair of a public and private key. The keys are bound with the application’s policy and the VM’s integrity. Each tenant uses the public key to verify that he interacts with his VM controlled by the integrity-enforced hypervisor.

Listing 1 shows an example of a security policy. The policy is a text file containing a whitelist of the hardware TPM manufacturer’s certificate chain (line 2), DRTM integrity measurements of the host kernel (lines 6–9), integrity measurements of the guest kernel (line 16), and legal runtime integrity measurements of the guest OS (lines 18–20). The certificate chain is used to establish trust in the underlying hardware TPM. WELES compares DRTM integrity measurements with PCR values certified by the TPM to ensure the correct hypervisor with enabled integrity-enforced mechanism was loaded. WELES uses
runtime integrity measurements to verify that only expected files and software have been loaded to the guest OS memory. A dedicated certificate (line 24) makes the integrity-enforcement practical because it permits more files to be loaded to the memory without redeploying the policy. Specifically, it is enough to sign software allowed to execute with the corresponding private key to let the software pass through the integrity-enforcement mechanism. Additional certificates (lines 12, 27) allow for OS updates [68].

4.3 Platform Bootstrap

The cloud provider is responsible for the proper machine initialization. She must turn on support for hardware technologies (i.e., TPM, DRTM, TEE), launch the hypervisor, and start Weles. Tenants detect if the platform was correctly initialized when they establish trust in the platform (§4.5).

First, Weles establishes a connection with the hardware TPM using the TPM attestation; it reads the TPM certificate and generates an attestation key following the activation of credential procedure ([16] p. 109-111). Weles ensures it communicates with the local TPM using [84], but other approaches might be used as well [33, 69]. Eventually, Weles reads the TPM quote, which certifies the DRTM launch and the measurements of the hypervisor’s integrity.

4.4 VM Launch

The cloud provider requests the hypervisor to spawn a new VM. The hypervisor allocates the required resources and starts the VM providing it with TPM access. At the end of the process, the cloud provider shares the connection details with the tenant, allowing the tenant to connect to the VM.

Weles emulates multiple TPMs inside the TEE because many VMs cannot share a single hardware TPM [19]. When requested by the hypervisor, Weles spawns a new TPM instance accessible on a unique TCP port. The hypervisor connects to the emulated TPM and exposes it to the VM as a standard character device. We further use the term emulated TPM to describe a TEE-based TPM running inside the hypervisor and distinguishing it from the software-based TPM proposed by the vTPM design.

### Listing 1: Example of the Weles’s security policy

```plaintext
host:
  tpm: |
  -----BEGIN CERTIFICATE-----
  # Manufacturer CA certificate
  -----END CERTIFICATE-----
  drtm: # measurements provided by the DRTM
    - {id: 17, sha256: f9ad0...cb}
    - {id: 18, sha256: c2c1a...c1}
    - {id: 19, sha256: a1be7...00}
  certificate: |
    -----BEGIN CERTIFICATE-----
    # software update certificate
    -----END CERTIFICATE-----
  guest:
    enforcement: true
    measurements: # legal integrity measurement digests
      - "e0a11...2a" # SHA digest over a startup script
      - "3a10b...bb" # SHA digest over a library
    certificate:
      |
        -----BEGIN CERTIFICATE-----
        # certificate of the signer, e.g., OS updates
        -----END CERTIFICATE-----
```

The communication between the hypervisor and the emulated TPM is susceptible to MitM attacks. Unlike Weles, the hypervisor does not execute inside the TEE, preventing Weles from using the TEE attestation to verify the hypervisor identity. However, Weles confirms the hypervisor identity by requesting it to present a secret when establishing a connection. Weles generates a secret inside the TEE and seals it to the hardware TPM via an encrypted channel ([10] §19.6.7). Only software running on the same OS as Weles can unseal the secret. Thus, it is enough to check if only trusted software executes on the platform to verify that it is the legitimate hypervisor who presents the secret.

Figure 4 shows the procedure of attaching an emulated TPM to a VM. Before the hypervisor spawns a VM, it commands Weles to emulate a new software-based TPM (1). Weles creates a new emulated TPM, generates a secret, and seals the secret with the hardware TPM (2). Weles returns the TCP port and the sealed secret to the hypervisor. The hypervisor unseals the secret from the hardware TPM (3) and establishes a TLS connection to the emulated TPM authenticating itself with the secret (4). At this point, the hypervisor spawns a VM. The VM boots up, the firmware and IMA send integrity measurements to the emulated TPM (5). To protect against...
Figure 4: Attachment of an emulated TPM to a VM. WELES emulates TPMs inside the TEE. Each emulated TPM is accessible via a TLS connection. To prevent the MitM attack, WELES authenticates the connecting hypervisor by sharing with him a secret via a hardware TPM. To mitigate the rollback attack, the emulated TPM increments the monotonic counter value on each non-idempotent command.

The rollback attack, each integrity measurement causes the emulated TPM to increment the hardware-based monotonic counter (MC) and store the current MC value inside the emulated TPM memory. To prevent the attach-
mittance of multiple VMs to the same emulated TPM, WELES permits a single client connection and does not permit reconnections. An attack in which an adversary redirects the hypervisor to a fake emulated TPM exporting a false secret is detected when establishing trust with the VM (§4.5).

4.5 Establish Trust

The tenant establishes trust with the VM in three steps. First, he verifies that WELES executes inside the TEE and runs on genuine hardware (a CPU providing the TEE functionality). He then extends trust to the hypervisor and VM by leveraging WELES to verify and enforce the host and guest OSes’ runtime integrity. Finally, he connects to the VM, ensuring it is the VM provisioned and controlled by WELES.

Since the WELES design does not restrict tenants to possess any vendor-specific hardware and the existing TEE attestation protocols are not standardized, we propose to add an extra level of indirection. Following the existing solutions [39], we rely on a trusted certificate authority (CA) that performs the TEE-specific attestation before signing an X.509 certificate confirming the WE-

Figure 5: The high-level view of the attestation protocol. WELES generates a SSH public/private key pair inside the TEE. The tenant receives the public key as a result of the policy deployment. To mitigate the MitM attacks, the tenant challenges the VM to prove it has access to the private key. WELES signs the challenge on behalf of the VM if and only if the platform integrity conforms with the policy.

LES’s integrity and the underlying hardware genuineness. The tenant establishes trust with WELES during the TLS-handshake, verifying that the presented certificate was issued to WELES by the CA.

Although the tenant remotely ensures that WELES is trusted, he has no guarantees that he connects to his VM controlled by WELES because the adversary can spoof the network [91] to redirect the tenant’s connection to an arbitrary VM. To mitigate the threat, WELES generates a secret and shares it with the tenant and the VM. When the tenant establishes a connection, he uses the secret to authenticate the VM. Only the VM which integrity conforms to the policy has access to this secret.

Figure 5 shows a high-level view of the protocol. First, the tenant establishes a TLS connection with WELES to deploy the policy (1). WELES verifies the platform integrity against the policy (2), and once succeeded, it generates the SSH key pair (3). The public key is returned to the tenant (4) while the private key remains inside the TEE. WELES enforces that only a guest OS which runtime integrity conforms to the policy can use the private key for signing. Second, the tenant initializes an SSH connection to the VM, expecting the VM to prove the possession of the SSH private key. The SSH client requests the SSH server running inside the VM to sign a challenge (5). The SSH server delegates the signing operation to WELES (6). WELES signs the challenge using the private key (7) if and only if the hypervisor’s and VM’s integrity match the policy. The SSH private key never leaves WELES; only a signature is returned to the SSH server (8). The SSH client verifies the signature using the SSH public key ob-
tained by the tenant from **WELES** (9). The SSH server also authenticates the tenant, who proves his identity using his own private SSH key. The SSH server is configured to trust his SSH public key. The tenant established trust in the remote platform as soon as the SSH handshake succeeds.

### 4.6 Policy Enforcement

**WELES** policy enforcement mechanism guarantees that the VM runtime integrity conforms to the policy. At the host OS, **WELES** relies on the IMA integrity-enforcement [43] to prevent the host kernel from loading to the memory files that are not digitally signed. Specifically, each file in the filesystem has a digital signature stored inside its extended attribute. IMA verifies the signature issued by the cloud provider before the kernel loads the file to the memory. The certificate required for signature verification is loaded from initramfs (measured by the DRTM) to the kernel’s keyring. At the guest OS, IMA inside the guest kernel requires the **WELES** approval to load a file to the memory. The emulated TPM, controlled by **WELES**, returns a failure when IMA tries to extend it with measurement not conforming to the policy. The failure instructs IMA not to load the file.

![Figure 6](image-url) The overview of the **WELES** prototype implementation.

#### memory corruption mitigation techniques. Those techniques help mitigate the consequences of, for example, buffer overflow attacks that might lead to privilege escalation or arbitrary code execution. To restrict the host from accessing guest memory and state, we follow existing security-oriented commercial solutions [28] that disable certain hypervisor features, such as hypervisor-initiated memory dump, huge memory pages on the host, memory swapping, memory ballooning through a virtio-balloon device, and crash dumps. For production implementations, we propose to rely on microkernels like formally proved seL4 [56].

We rely on SGX as the TEE technology. The SGX remote attestation [48] allows us to verify if the application executes inside an enclave on a genuine Intel CPU. Other TEEs might be supported (§7). We implemented **WELES** in Rust [63], which preserves memory-safety and typesafety. To run **WELES** inside an SGX enclave, we use the SCONE framework [15] and its Rust cross-compiler. We also exploit the Intel trusted execution technology (TXT) [38] as a DRTM technology because it is widely available on Intel CPUs. We use the open-source software tboot [12] as a pre-kernel bootloader that establishes the DRTM with TXT to provide the measured boot of the Linux kernel.

### 5 Implementation

#### 5.1 Technology Stack

We decided to base the prototype implementation on the Linux kernel because it is an open-source project supporting a wide range of hardware and software technologies. It is commonly used in the cloud and, as such, can demonstrate the practicality of the proposed design. QEMU [17] and kernel-based virtual machine (KVM) [55] permit to use it as a hypervisor. We rely on Linux IMA [78] as an integrity enforcement and auditing mechanism built-in the Linux kernel.

We chose Alpine Linux because it is designed for security and simplicity in contrast to other Linux distributions. It consists of a minimum amount of software required to provide a fully-functional OS that permits keeping a trusted computing base (TCB) low. All userspace binaries are compiled as position-independent executables with stack-smashing protection and relocation read-only

![Intel SGX enclaves](image-url)

**WELES**: monotonic counter service

- **WELES**: emulated TPM
- **WELES**: monitoring service
- Intel trusted execution technology (TXT)
- Intel software guard extensions (SGX)
- TPM 2.0

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**VM**: SSH server, Linux, IMA

**QEMU**

**Alpine Linux**

**Linux kernel**

**Intel SGX enclaves**

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#### 5.2 Prototype Architecture

The **WELES** prototype architecture consists of three components executing in SGX enclaves: the monitoring service, the emulated TPM, and the monotonic counter service.
The monitoring service is the component that leverages Linux IMA and the hardware TPM to collect integrity measurements of the host OS. There is only one monitoring service running per host OS. It is available on a well-known port on which it exposes a TLS-protected REST API used by tenants to deploy the policy. We based this part of the implementation on [84] that provides a mechanism to detect the TPM locality. The monitoring service spawns emulated TPMs and intermediates in the secret exchange between QEMU and the emulated TPM. Specifically, it generates and seals to the hardware TPM the secret required to authenticate the QEMU process, and passes this secret to an emulated TPM.

The emulated TPM is a software-based TPM emulator based on the libtpms library [18]. It exposes a TLS-based API allowing QEMU to connect. The connection is authenticated using the secret generated inside an SGX enclave and known only to processes that gained access to the hardware TPM. We extracted the emulated TPM into a separate component because of the libtpms implementation, which requires running each emulator in a separate process.

The monotonic counter service (MCS) provides access to a hardware monotonic counter (MC). Emulated TPMs use it to protect against rollback attacks. We designed the MCS as a separate module because we anticipate that due to hardware MC limitations (i.e., high latency, the limited number of memory overwrites [82]), a distributed version, e.g., ROTE [62], might be required. Notably, the MCS might also be deployed locally using SGX MC [22] accessible on the same platform where the monitoring service and emulated TPM run.

The emulated TPM establishes trust with the MCS via the TLS-based SGX attestation (§5.4) and maintains the TLS connection open until the emulated TPM is shutdown. We implemented the emulated TPM to increase the MC before executing any non-idempotent TPM command, e.g., extending PCRs, generating keys, writing to non-volatile memory. The MC value and the TLS credentials are persisted in the emulated TPM state, which is protected by the SGX during runtime and at rest via sealing. When the emulated TPM starts, it reads the MC value from the MCS and then checks the emulated TPM state freshness by verifying that its MC value equals the value read from the MCS.

5.3 Monotonic Counter Service

We implemented a monotonic counter service (MCS) as a service executed inside the SGX enclave. It leverages TPM 2.0 high-endurance indices [10] to provide the MC functionality. The MCS relies on the TPM attestation to establish trust with the TPM chip offering hardware MC, and on the encrypted and authenticated communication channel (§10 §19.6.7) to protect the integrity and confidentiality of the communication with the TPM chip from the enclave. The MCS exposes a REST API over a TLS (§5.4), allowing other enclaves to increment and read hardware monotonic counters remotely.

5.4 TLS-based SGX Attestation

We use the SCONE key management system (CAS) [5] to perform remote attestation of WELES components, verify SGX quotes using Intel attestation service (IAS) [14], generate TLS credentials, and distribute the credentials and the CAS CA certificate to each component during initialization. WELES components are configured to establish mutual authentication over TLS, where both peers present a certificate, signed by the same CAS CA, containing an enclave integrity measurement. Tenants do not perform the SGX remote attestation to verify the monitoring service identity and integrity. Instead, they verify the certificate exposed by a remote peer during the policy deployment when establishing a TLS connection to the monitoring service. The production implementation might use Intel SGX-RA [57] to achieve similar functionality without relying on an external key management system.

5.5 VM Integrity Enforcement

The current Linux IMA implementation extends the integrity digest of the IMA log entry to all active TPM PCR banks. For example, when there are two active PCR banks (e.g., SHA-1 and SHA-256), both are extended with the same value. We did a minor modification of the Linux kernel. It permitted us to share with the emulated TPM not only the integrity digest but also the file’s measurement and the file’s signature. We modified the content of the PCR_Extend command sent by the Linux IMA in a way it uses the SHA-1 bank to transfer the integrity digest, the SHA-256 bank to transfer the file’s measurement
digest, and the SHA-512 bank to transfer the file’s signature. In the emulated TPM, we intercept the PCR_extend command to extract the file’s measurement and the file’s digest. We use obtained information to enforce the policy; if the file is not permitted to be executed, the emulated TPM process closes the TLS connection causing the QEMU process to shut down the VM.

5.6 SSH Integration

To enable a secure connection to the VM, we relied on the OpenSSH server. It supports the PKCS#11 [66] standard, which defines how to communicate with cryptographic devices, like TPM, to perform cryptographic operations using the key without retrieving it from the TPM.

We configured an OpenSSH server running inside the guest OS to use an SSH key stored inside the emulated TPM running on the host OS. The VM’s SSH private key is generated and stored inside the SGX enclave, and it never leaves it. The SSH server, via PCRS#11, uses it for the TLS connection only when WELES authorizes access to it. The tenant uses his own SSH private key, which is not managed by WELES.

6 Evaluation

We present the evaluation of WELES in three parts. In the first part, we measure the performance of internal WELES components and related technologies. In the second part, we check if WELES is practical to protect popular applications, i.e., nginx, memcached. Finally, we estimate the TCB of the prototype used to run the experiments mentioned above.

**Testbed.** Experiments execute on a rack-based cluster of Dell PowerEdge R330 servers equipped with an Intel Xeon E3-1270 v5 CPU, 64 GiB of RAM, Infineon 9665 TPM 2.0 discrete TPM chips (dTPMs). Experiments that use an integrated TPM (iTPM) run on Intel NUC7i7BNH machine, which has the Intel platform trusted technology (PTT) [25] running on Intel ME 11.8.50.3425 powered by Intel Core i7-7567U CPU and 8 GiB of RAM. All machines have a 10 Gb Ethernet network interface card (NIC) connected to a 20 Gb/s switched network. The SGX, TXT, TPM 2.0, Intel virtualization technology for directed I/O (VT-d) [24], and single root input/output virtualization (SR-IOV) [23] technologies are turned on in the UEFI/BIOS configuration. The hyper-threading is switched off. The enclave page cache (EPC) is configured to reserve 128 MiB of random-access memory (RAM).

On host and guest OSes, we run Alpine 3.10 with Linux kernel 4.19. We modified the guest OS kernel according to the description in §5.5. We adjusted quick emulator (QEMU) 3.1.0 to support TLS-based communication with the emulated TPM as described in §4.4 CPUs are on the microcode patch level (0x5e).

6.1 Micro-benchmarks

**Are TPM monotonic counters practical to handle the rollback protection mechanism?** Strackx and Piessens [82] reported that the TPM 1.2 memory gets corrupted after a maximum of 1.450M writes and has a limited increment rate (one increment per 5 sec). We run an experiment to confirm or undermine the hypothesis that those limitations apply to the TPM 2.0 chip. We were continuously incrementing the monotonic counter in the dTPM and the iTPM chips. The dTPM chip reached 85M increments, and it did not throttle its speed. The iTPM chip slowed down after 7.3M increments limiting the increment latency to 5 sec. We did not observe any problem with the TPM memory.

**What is the cost of the rollback protection mechanism?** Each non-idempotent TPM operation causes the emulated TPM to communicate with the MCS and might directly influence the WELES performance. We measured the latency of the TPM-based MCS read and increment operations. In this experiment, the MCS and the test client execute inside an SGX enclave. Before the experiment, the test client running on the same machine establishes a TLS connection with the MCS. The connection is maintained during the entire experiment to keep the communication overhead minimal. The evaluation consists of sending 5k requests and measuring the mean latency of the MCS response.

**Table 1:** The latency of main operations in the TPM-based MCS. \( \sigma \) states for standard deviation.

|                      | Read   | Increase |
|----------------------|--------|----------|
| discrete TPM         | 42 ms  | 40 ms    |
| integrated TPM       | 25 ms  | 32 ms    |
Table 1 shows that the MCS using iTPM performs from $1.25 \times$ to $1.68 \times$ faster than its version using dTPM. The read operation on the iTPM is faster than the increment operation (25 ms versus 32 ms, respectively). Differently, on dTPM both operations take a similar amount of time (about 40 ms).

What is the cost of running the TPM emulator inside TEE and with the rollback protection mechanism? Is it slower than a hardware TPM used by the host OS? As a reference point to evaluate the emulated TPM’s performance, we measured the latency of various TPM commands executed in different implementations of TPMs. The TPM quotes were generated with the elliptic curve digital signature algorithm (ECDSA) using the P-256 curve and SHA-256 bit key. PCRs were extended using the SHA-256 algorithm. Figure 7 shows that except for the PCR extend operation, the SGX-based TPM with rollback protection is from $1.2 \times$ to $69 \times$ faster than hardware TPMs and up to $6 \times$ slower than the unprotected software-based swTPM. Except for the create primary command, which derives a new key from the TPM seed, we did not observe performance degradation when running the TPM emulator inside an enclave. However, when running with the rollback protection, the TPM slows down the processing of non-idempotent commands (e.g., PCR_Extend) due to the additional time required to increase the MC.

How much IMA impacts file opening times? Before the kernel executes the software, it verifies if executable, related configuration files, and required dynamic libraries can be loaded to the memory. The IMA calculates a cryptographic hash over each file (its entire content) and sends the hash to the TPM. We measure how much this process impacts the opening time of files depending on their size. Figure 8 shows that the IMA inside the guest OS incurs higher overhead than the IMA inside the host OS. It is primarily caused by i) the higher latency of the TPM extend command ($\sim 43$ ms) that is dominated by a slow network-based monotonic counter, ii) the IMA mechanism itself that has to calculate the cryptographic hash over the entire file even if only a small part of the file is actually read, and iii) the less efficient data storage used by the VM (virtualized storage, QCOW format). In both systems, the IMA takes less than 70 ms when loading files smaller than 1 MB (99% of files in the deployed prototype are smaller than 1 MB). Importantly, IMA measures the file only once unless it changes. Figure 8 shows that the next file reads take less than 40 $\mu$s regardless of the file size.

6.2 Macro-benchmarks
We run macro-benchmarks to measure performance degradation when protecting popular applications, i.e., the nginx web-server [4] and the memcached cache system [2], with WELES. We compare the performance of four variants for each application running on the host operating system (OS) (native), inside a SCONE-protected Docker container on the host OS (SCONE), inside a guest OS (VM), inside a WELES-protected guest OS with rollback protection turned on (WELES). Notably, WELES operates under a weaker threat model than SCONE. We compare them to show the tradeoff between the security and performance.

How much does WELES influence the throughput of
**Figure 9:** Throughput/latency of the nginx web server. We configured nginx to run a single worker thread with turned off gzip compression and logging, according to available SCONE’s benchmark settings. Then, we used wrk2 [85], running on a different physical host, to simulate 16 clients (4 per physical core) concurrently fetching a pre-generated 10 KiB binary uncompressed file for 45 s. We were increasing the frequency of the fetching until the response times started to degrade. Except for the reference measurement (native) run on the bare metal, nginx run inside a VM with access to all available cores and 4 GB of memory. SCONE variant reached about 31k requests, which is 0.45× of the native throughput. We observed low-performance degradation incurred by the virtualization (less than 2%). The WELES overhead is caused mostly by the IMA.

**Does WELES influence the throughput of systems that extensively use in-memory storage, i.e., memcached?** We used memtier [59] to generate load by sending GET/SET requests (1:1 ratio) of 500 bytes of random data to a memcached instance running on a different physical host. We calculated the memcached performance by computing the mean throughput achieved by the experiment before the throughput started to degrade (latency <2 ms). Except for the reference measurement (native) run on the bare metal, memcached run in a VM with access to all available cores and 4 GB of memory. **Figure 10** shows WELES influence on the throughput-latency ratio of memcached. We observed low performance degradation when running memcached in a VM. WELES achieved 0.98× of the native throughput. It is a result of IMA implementation, which measures the integrity of the memcached executables and configuration files during memcached launch, but it does not measure data directly written to the memory during runtime. WELES throughput was 1.23× higher than the memcached run inside SCONE.

**How the measured boot increases the VM boot time?** Table 2 shows how WELES impacts VM boot times. As a reference, we measure the boot time of a VM without any TPM attached. Then, we run experiments in which a VM has access to different implementations of a software-based TPMs. Except for the reference measurement, the Linux IMA is always turned on. Each VM has access to all available cores and 4 GB of memory. As the guest OS, we run Ubuntu 18.10, a Linux distribution with a pre-installed tool (systemd-analyze) to calculate system boot times. The measured boot increases the VM load time. It is caused by the IMA module that measures files required to initialize the OS. We did not observe any difference in boot time between the setup with the swTPM [6] and the WELES emulated TPM (WELES no MC). However, when running the emulated TPM with the rollback protection (WELES with MC), the VM boot time is 5.2× and 3.6× higher when compared to the reference and the swTPM setting, respectively. Alternative implementations

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**Table 2:** The VM boot time duration when using different TPM implementations: no TPM, swTPM [6], emulated TPM inside an SGX enclave without rollback protection (WELES TPM), and emulated TPM inside an SGX enclave with rollback protection (WELES TPM with MC). σ states for standard deviation.

| MC | TPM | IMA | Boot time |
|----|-----|-----|-----------|
| no TPM | × | × | 9.7 s (σ = 0.1 s) |
| swTPM | × | ✓ | 14.0 s (σ = 0.2 s) |
| WELES no MC | × | ✓ | 14.1 s (σ = 0.3 s) |
| with MC | ✓ | ✓ | 50.8 s (σ = 0.4 s) |
| fast MC | ✓ | ✓ | 15.8 s (estimate) |

1 The limited network bandwidth dictated the file size. For larger size we saturated the NIC bandwidth.
6.3 Trusted Computing Base

As part of this evaluation, we estimate the TCB of software components by measuring the source code size (using source lines of code (SLOC) as a metric) used to build the software stack.

How much does the WELES increase the TCB? We estimate the software stack TCB by calculating size of the source code metrics using CLOC [32], lib.rs [1], and Linux stat utility. For the Linux kernel and QEMU, we calculated code that is compiled with our custom configuration, i.e., Linux kernel with support for IMA and KVM, and QEMU with support for gnutls, TPM and KVM.

To estimate the TCB of nginx and memcached executed with WELES, we added their source code sizes (including musl libc) to the source code size of the software stack required to run it (92.49 MB). Table 3 shows that the evaluated setup increases the TCB 13× and 32× for nginx and memcached, respectively. When compared to SCONE, WELES prototype increases the TCB from 8× to 12×. SCONE offers not only stronger security guarantees (confidentiality of the tenant’s code and data) but also requires to trust a lower amount of software code. However, this comes at the cost of performance degradation (§6.2) and the necessity of reimplementing or at least recompiling a legacy application to link with the SCONE runtime.

7 Discussion

7.1 Alternative TEEs

The WELES design (§4) requires a TEE that offers a remote attestation protocol and provides confidentiality and integrity guarantees of WELES components executing in the host OS. Therefore, the SGX used to build the WELES prototype (§5) might be replaced with other TEEs. In particular, WELES implementation might leverage Sanctum [30], Keystone [60], Flicker [65], or L4Re [73] as an SGX replacement. WELES might also leverage ARM TrustZone [?] by running WELES components in the secure world and exploiting the TPM attestation to prove its integrity.

7.2 Hardware-enforced VM Isolation

Hardware CPU extensions, such as AMD secure encrypted virtualization (SEV) [45], Intel multi-key total memory encryption (MKTME) [26], Intel trust domain extensions (TDX) [27], are largely complementary to the WELES design. They might enrich WELES design by providing the confidentiality of the code and data against rogue operators with physical access to the machine, compromised hypervisor, or malicious co-tenants. They also consider untrusted hypervisor excluding it from the WELES TCB. On the other hand, WELES complements these technologies by offering means to verify and enforce the runtime integrity of guest OSes. Functionality easily
available for bare-metal machines (via a hardware TPM) but not for virtual machines.

7.3 Trusted Computing Base

The prototype builds on top of software commonly used in the cloud, which has a large TCB because it supports different processor architectures and hardware. WELES might be combined with other TEE and hardware extensions, resulting in a lower TCB and stronger security guarantees. Specifically, WELES could be implemented on top of a microkernel architecture, such as formally verified seL4 [56, 71], that provides stronger isolation between processes and a much lower code base (less than 10k SLOC [56]), when compared to the Linux kernel. Comparing to the prototype, QEMU might be replaced with Firecracker [13], a virtual machine monitor written in a type-safe programming language that consists of 46k SLOC (0.16× of QEMU source code size) and is used in production by Amazon AWS cloud. The TCB of the prototype implementation might be reduced by removing superfluous code and dependencies. For example, most of the TPM emulator functionalities could be removed following the approach of μTPM [64]. WELES API could be built on top of the socket layer, allowing removal of HTTP dependencies that constitute 41% of the prototype implementation code.

7.4 Integrity Measurements Management

The policy composed of digests is sensitive to software updates because newer software versions result in different measurement digests. Consequently, any software update of an integrity-enforced system would require a policy update, which is impractical. Instead, WELES supports dedicated update mirrors serving updates containing digitally signed integrity measurements [68, 21]. Other measurements defined in the policy can be obtained from the national software reference library [3] or directly from the IMA-log read from a machine executed in a trusted environment, e.g., development environment running on tenant premises. The amount of runtime IMA measurements can be further reduced by taking into account processes interaction to exclude some mutable files from the measurement [47, 79].

8 Related work

VM attestation is a long-standing research objective. The existing approaches vary from VMs monitoring systems focusing on system behavior verification [42, 76, 70], intrusion detection systems [49, 77], or verifying the integrity of the executing software [35, 20]. WELES focuses on the VM runtime integrity attestation. Following Terra [35] architecture, WELES leverages VMs to provide isolated execution environments constrained with different security requirements defined in a policy. Like Scalable Attestation [20], WELES uses software-based TPM to collect VM integrity measurements. WELES extends the software-based TPM functionality by enforcing the policy and binding the attestation result with the VM connection, as proposed by IVP [80]. Unlike the idea of linking the remote attestation quote to the TLS certificate [37], WELES relies on the TEE to restrict access to the private key based on the attestation result. Following TrustVisor [64], WELES exposes trusted computing methods to legacy applications by providing them with dedicated TPM functionalities emulated inside the hypervisor. Unlike others, WELES addresses the TPM cuckoo attack at the VM level by combining integrity enforcement with key management and with the TEE-based remote attestation. Alternative approaches to TPM virtualization exist [83, 36]. However, the cuckoo attack remains the main problem. WELES enhances the vTPM design [19] mostly because of the simplicity; no need for hardware [83] or the TPM specification [36] changes.

Hardware solutions, such as SEV [45], IBM PEF [44], TDX [27], emerged to isolate VMs from the untrusted hypervisor and the cloud administrator. However, they lack the VM runtime integrity attestation, a key feature provided by WELES. WELES is complementary to them. Combining these technologies allows for better isolation of VM from the hypervisor and the administrator and for runtime integrity guarantees during the VM’s runtime.

9 Conclusion

This paper presented WELES, the virtual machine (VM) attestation protocol allowing for verification that security-sensitive applications execute in the VM composed and controlled by expected software in expected configura-
tion. WELES provides transparent support for legacy applications, requires no changes in the VM configuration, and permits tenants to remotely attest to the platform runtime integrity without possessing any vendor-specific hardware by binding the VM state to the SSH connection. WELES complements hardware-based trusted execution environment (TEE), such as AMD SEV, IBM PEF, Intel TDX, by providing runtime integrity attestation of the guest OS. Finally, WELES incurs low performance overhead ($\leq 6\%$) but has much larger trusted computing base (TCB) compared to pure TEE approaches, such as Intel software guard extensions (SGX).

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