Trust Management as a Service:
Enabling Trusted Execution in the Face of Byzantine Stakeholders

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Abstract—Trust is arguably the most important challenge for critical services both deployed as well as accessed remotely over the network. These systems are exposed to a wide diversity of threats, ranging from bugs to exploits, active attacks, or simply careless administrators. To protect such applications, one needs to guarantee that they are properly configured and securely provisioned with the “secrets” (e.g., encryption keys) necessary to preserve not only the confidentiality, integrity and freshness of their data but also their code. Furthermore, these secrets should not be kept under the control of a single stakeholder—which might be compromised and would represent a single point of failure—and they must be protected across software versions in the sense that attackers cannot get access to them via malicious updates. Traditional approaches for solving these challenges often use ad hoc techniques and ultimately rely on a hardware security module (HSM) as root of trust. We propose a more powerful and generic approach to trust management that instead relies on trusted execution environments (TEEs) and a set of stakeholders as root of trust. Our system, PALÆMON, can operate as a managed service deployed in an untrusted environment, i.e., one can delegate its operations to an untrusted cloud provider with the guarantee that data will remain confidential despite not trusting any individual human (even with root access) nor system software. PALÆMON addresses in a secure, efficient and cost-effective way five main challenges faced when developing trusted networked applications and services. Our evaluation on a range of benchmarks and real applications shows that PALÆMON performs efficiently and can protect secrets of services without any change to their source code.

I. INTRODUCTION

Protecting the confidentiality, integrity and freshness (CIF) of application data is a key challenge of many applications, and a primary reason for companies to be wary of deploying their system outside premises in shared environments. To illustrate the challenges faced in such scenarios, consider for instance modern machine learning applications that require significant computing power and would hence benefit from running in a scalable cloud infrastructure. Yet, at the same time, they need to protect their code, their training data (input) and the produced model (output), all of which represent key assets for their respective owners (see Fig. 1). The development and operation of such a large system involve multiple stakeholders, notably software developers, system administrators, data providers and cloud providers, which cannot necessarily be trusted and might collude to gain advantages over the other stakeholders [56]. For example, we cannot trust that system administrators or software developers will neither leak [65], [26] nor modify application code and data. To address these challenges and enable trusted application execution in the face of Byzantine stakeholders, we have designed PALÆMON, a trust management service that builds on top of the SCONE platform [5] and ultimately relies on hardware-based trusted execution environments (TEEs) for secure execution.

Fig. 1: Components and stakeholders of the machine learning (ML) use case. The training data and model belong to the data and model providers, whereas the ML processing runtime is owned by the software provider. Key assets must be protected at all times from other stakeholders.

PALÆMON was originally developed in order to address real problems from some users and there was no alternative service available to solve the problems we faced. It was extended and refined over the course of the last two years to take into account additional threats and support the evolution of trusted applications via secure updates. We motivate its design and illustrate its operation on a real-life production use case in the machine learning space, yet our approach is more general and applies to a much wider range of applications.

At the core of PALÆMON is a trust management service specifically designed to address the following main challenges:
1) Secret management — How can we securely provide applications with secrets in an untrusted environment?
2) Managed operation — How can we delegate the management of PALÆMON to untrusted stakeholders?
3) Robust root of trust — How can we protect CIF against malicious stakeholders?
4) Rollback protection — How can we ensure freshness of data and code in an efficient manner?
5) Secure update — How can we support secure updates of applications and PALÆMON?

To better understand the importance of these challenges, let us illustrate them on one of the original use cases that guided the design of PALÆMON. This real-life use case comes from a company, a software provider specialized in ML that develops its ML engine in Python (see Fig. 1). The engine is executed by a second party, the model provider, which processes training data to produce a model. The software provider must neither learn the training data nor the produced model. Conversely, the model provider must not learn the application code of the software provider. Moreover, the software provider may want to limit the number of models produced by its application, and hence the number of times the code is executed. The model provider might try to circumvent this limitation by reverting the application to a previous state in order to generate more models (“rollback attack”).
In its initial deployment, the model provider ran the ML engine on dedicated computers within its own air-gapped infrastructure, over which it has complete control. Then, the model provider wants to execute the application in a cloud instead. Therefore, it also needs to protect its training data and generated models from the third-party cloud provider, including developers and system administrators. Finally, when operating in the untrusted cloud, it should be possible for the software provider as well as the provider of the Python runtime to continuously update their software while preserving the trust guarantees, i.e., one should prevent an attacker from injecting malicious code during software updates.

This real-life application illustrates the need for addressing the aforementioned set of problems: it requires secure secret management to preserve confidentiality of the code and data, managed operation to delegate the management to a cloud provider, a robust root of trust to protect both data and code, rollback protection to control the number of models produced, and support for secure update for managing the life cycle of software deployed in a third-party cloud. Our general approach to address these five problems is to define a novel trust management service (TMS) that supports security policies and is able to deal with untrusted stakeholders. The TMS can itself be managed by an untrusted entity (e.g., the ML model provider) while still being trusted by other entities (e.g., the ML software provider).

The contributions of this paper are as follows. While many of the techniques that we use are known, combining these to address the problems we face is novel. We are not aware of any other service that transparently protects applications from rollback attacks with little overheads, supports secure software updates and guarantees CIF of data and code even in the face of insider attacks, while still being able to delegate the management of the service to remote providers. Throughput of our monotonic counters is 5 orders of magnitude higher than those provided by the SGX platform.

The remainder of the paper is organized as follows. We first introduce the threat model and problem in §II. We then present the architecture of PALEMON in §III and its implementation in §IV. We evaluate PALEMON’s security and performance in §V, present a real use case in production settings in §VI, discuss related work in §VII and conclude in §VIII.

II. THREATS AND CHALLENGES

We first introduce our threat model before we describe in greater details the challenges addressed by PALEMON.

A. Threat Model

Services executing in untrusted environments such as clouds are vulnerable to attackers with root privileges. Attackers often target the credentials of system administrators to gain access to hosts [76], [28], [24]. They also exploit bugs in the system software to gain root privileges on systems [30], [21].

Multiple stakeholders of the same services cannot trust each other to protect the CIF of their digital assets such as data and code. Fig. 2 illustrates the security goals of PALEMON with regard to the stakeholders as well as the building blocks in our system. For example, PALEMON can protect CIF of Python code deployed at remote sites, a somewhat surprising but popular requirement for several applications of our users. Furthermore, applications must be regularly updated, and we need to protect them against malicious software updates triggered by attackers.

Note that we cannot trust any system administrator or software developer—actually not any single individual. Hence, we do not trust in CIF of main memory. We also do not assume that the OS-based access control can ensure CIF since a single malicious system administrator could break this assumption. It follows that one cannot trust software updates originating from a single developer nor security policies defined by any individual, independent of their authorization level or trustworthiness.

PALEMON protects from attempts to compromise CIF of code and data by requiring a quorum of trusted entities—not just a single individual—to approve any given change. This is based on the assumption that, in any organization that must securely operate an application, one can identify a set of $n$ stakeholders and a threshold $f$ (with $f<n$), such that $n−f$ stakeholders can be trusted at any point in time, i.e., at most $f$ of them exhibit Byzantine behaviour because of neglect or malicious intent. Hence, if at least $f+1$ stakeholders approve a change, such as a software update, at least one of them judged it to be trustworthy. In practice, the typical convention is that any policy change must be approved by all members, i.e., stakeholders in a legal business contract. A single member can choose to decline and in this way prevent malicious policy changes.

TEEs such as Intel software guard extensions (SGX) are typically vulnerable to side-channel attacks [11], [47], [20], [71], [73]. Such attacks can be addressed using existing techniques (e.g., Varys [59]) and are out of the scope of this work. Similarly, we do not consider denial of service attacks.

In our threat model, we anticipate that new attacks on TEEs can appear in the future. We assume that we can put mitigation measures either in software or in microcode, or by limiting execution to certain CPU types and features not vulnerable to these attacks. This implies that we need to be able to continuously update PALEMON as well as the applications and deactivate vulnerable instances within a short period of time, so that the system is protected against new attacks.

B. Problem Statement

We now introduce a more detailed definition of the problem, along with five challenges identified when analysing and operating a wide range of real-world applications that we briefly introduced earlier, with regard to our ML use case.

Secret management — Legacy software can use program arguments, environment variables or files to obtain secrets, as can be observed in Table I, which shows a quick analysis of various popular services. To account for this diversity and provide seamless integration of secret management in legacy applications, we need to solve the problem of:

How to support secret management for common configuration approaches in a secure way and without requiring modifications to the source code?

Container images (e.g., Docker images) are a popular way to deploy applications. We want to be able to customize container images such that not only $(i)$ different application developers can inject different secrets in their derived application images, but also $(ii)$ one can inject different secrets in each container instance of an image (see Fig. 2). For example, a client running such an image might inject client-specific secrets for
the application to be able to decrypt client-encrypted input files. The injection mechanism must protect CIF in the sense that an adversary cannot read, modify or replace these secrets.

**Managed operation** — The behaviour of applications is not only determined by the application code, but also by its configuration parameters such as configuration files. Some applications could be configured in a way that can leak confidential data. Therefore, clients would need the ability to verify that an application is properly configured to ensure CIF of their data. This challenge is especially critical for PALEMON, as it manages secrets on behalf of clients while operating in a different administrative domain. Therefore, in this paper, we address the problem of:

How to delegate the management of applications, as well as PALEMON instances, to untrusted providers while still ensuring CIF of the secrets?

**Robust root of trust** — In addition to cloud providers and system administrators, we do not trust insiders such as the software developers who build the software components, or the security experts who design the security policies. We must therefore solve the problem of:

How to guarantee CIF of data and code even in face of malicious insiders, i.e., in a Byzantine environment?

**Rollback protection** — Whereas cryptography can preserve confidentiality and integrity of data via encryption, it does not protect from the powerful class of “rollback” attacks by which a malicious party attempts to replace the current state of the file system with a previous version. In this way, they can revert data and undo some processing. In our ML use case, a client could roll back the file system to execute the application more often than permitted. Preventing rollbacks typically implies significant runtime overheads and application reengineering, which we want to avoid. The problem we address is hence:

How to protect applications from rollback attacks with only negligible overhead and without requiring modifications to the source code?

**Secure update** — Software needs to be updated continuously, not only for adding new features but more importantly to fix bugs and patch security vulnerabilities. We therefore need a secure approach to update applications, by making sure that the new versions are genuine before transferring the secrets of the previous version to the new one. Specifically:

How to update applications, as well as PALEMON itself, without compromising secrets even when facing a malicious software update initiated by an insider?

### Table I: How popular services obtain secrets (*∗*: evaluated in §V).

| Program     | Version | Lang. | Args. | Env. | Files |
|-------------|---------|-------|-------|------|-------|
| Consul      | 1.2.3   | Go    |       |      |       |
| MariaDB     | 10.1.26 | C/C++ |       |      |       |
| Memcached   | 1.5.6   | C     |       |      |       |
| MongoDB     | 4.0     | C++   |       |      |       |
| Nginx       | 2.4     | C     |       |      |       |
| PostgreSQL  | 10.5    |       |       |      |       |
| Redis       | 4.0.11  | C     |       |      |       |
| Vault       | 0.8.1   | Go    |       |      |       |
| WordPress   | 4.9.x   | PHP   |       |      |       |
| ZooKeeper   | 3.4.11  | Java  |       |      |       |

Moreover, this should be supported in settings where the management of PALEMON is delegated to an untrusted party that is permitted to perform the update.

### III. APPROACH: A TRUST MANAGEMENT SERVICE

Here we describe how PALEMON tackles the introduced problems above, with more technical descriptions also given in §IV.

#### A. Secret Management

One of the main roles of PALEMON is to pass secrets in a trusted manner to applications after attesting them. Each application is executed in a TEE and associated with a security policy that defines which applications can access which secrets on which hosts. Applications are identified by a cryptographic hash of the enclave [22] (MRE) and the content of the files they can access. Secrets are typed and can either be explicitly defined, or randomly chosen by PALEMON. Access to a security policy is guarded by a two-stage access control mechanism using a certificate and a policy board (see Fig. 3). One can define the access control and security policy in such a way that only applications under the control of the security policy can gain access to the secrets. In this way, one can prevent any stakeholder from accessing the secrets.

Secrets can be passed to applications as command line arguments, environment variables, or can be injected into files. The files can contain PALEMON variables referring to the names of secrets defined in the security policy. The variables are transparently replaced by the value of the secret when an application that is permitted to access the secrets reads the file. By transparently, we mean that the application is not aware of the replacement and its code does not need to be modified.

Secret management is supported through security policies, whose general structure is shown in Fig. 3. Each policy has a unique name and can define: (a) the permitted MRE of an application (several MREs can be specified to facilitate software updates); (b) the set of permitted platforms on which the application is permitted to run, or none if permitted to run on any platform; (c) the key and tag of the file system (the tag is a secure hash across all files, which are transparently en/decrypted with the key inside the TEE); (d) the command line arguments; (e) the environment variables; (f) a set of files to inject secrets into; and (g) imports/exports of secrets from/to other policies.

#### B. Managed PALEMON

Our objective is to support a feature that we can delegate the management of a PALEMON instance to an untrusted party, say a...
cloud provider, while the clients of PALÆMON can still trust that their secrets are safe and well protected. Note that the cloud provider has full control over what code it executes and might try to run variants of PALÆMON that are wrongly configured or have modified code. We ensure that clients connecting to a PALÆMON instance can attest it, i.e., they can verify that this instance runs the expected unmodified PALÆMON code. Moreover, this code does not support any configuration options that negatively influence the CIF of client data stored in the instance.

We support two ways to attest a PALÆMON instance (see Fig. 4): (i) using transport layer security (TLS) [29], [75]; and (ii) with explicit attestation. The TLS-based attestation requires a trusted certification authority (CA) with a known root certificate (RC). The CA first attests the PALÆMON instance using approach (ii) to ensure that this instance runs inside a TEE and has a correct MRE. Only then will the CA provide the instance with a certificate signed with the RC. The CA itself runs inside of a TEE and can be attested using explicit attestation. Entities that trust the CA can attest the instance by checking that its TLS certificate is signed by the RC.

To support software updates of PALÆMON itself, the CA includes a set of correct MREs. The CA only signs certificates for these MREs and also limits the duration of the certificates to ensure timely upgrades to new versions of PALÆMON. The set of MREs is stored inside of the CA’s binary, i.e., an adversary cannot modify the set without invalidating the MRE of the CA. Hence, deploying a new version of PALÆMON requires first to deploy a new version of the CA. Updates of the CA itself are controlled by a PALÆMON policy board consisting of a set of stakeholders and follow the procedure described in §III-E.

Clients might not trust the CA if they do not use the current set of valid MREs, e.g., they only trust code instances that have been deployed some time ago, or are not represented in the PALÆMON policy board. These clients need to attest the PALÆMON instance in the same way that the CA attests instances, as described in §IV-B. In practice, any updates of PALÆMON must be approved by all stakeholders.

C. Robust Root of Trust

Our threat model permits Byzantine behaviour of stakeholders like software developers and system administrators. Any change to an application or its configuration can impact the CIF of both data and code. PALÆMON therefore includes a mechanism to ensure that any security policy modification must be approved by at least $f+1$ stakeholders. To that end, a security policy can define a policy board and a threshold—typically set to $f+1$—of policy board members that must give approval for PALÆMON to permit any create, read, update and delete (CRUD) access to the policy. Upon creation, the board of the new policy must also approve the operation. In that way, any client can create policies as long as they have unique names, and the policy board agrees to take control over them.

Each policy board member is represented in the security policy by a certificate and a URL of an approval service, responsible to approve or reject accesses to the policy. Upon a client access, PALÆMON contacts the board members, verifies their certificates and asks them for approval of the request via a TLS-secured REST call to their approval service.

Approval services typically run inside TEEs. In case the associated board member is a person, they should perform a two-factor authentication with one being based on biometric identifiers. Approval services may also consist of services that check certain aspects of a policy, e.g., through source code analysis and verification of the MRE. In particular, a policy board member could be an organisation that validates software, i.e., perform checks on behalf of their clients to ensure that the software associated with a certain MRE can be trusted to protect the CIF of data.

Some policy board members can be given veto rights, i.e., they can unilaterally reject a policy change. For example, a data provider might only provide data to applications for which it is a policy member with veto rights. In that way, the data provider can ensure that policy changes will not result in data leakage.

D. Rollback Protection

We want to protect applications from rollback attacks without requiring their code to be changed. To that end, PALÆMON performs transparent encryption of files inside of the TEE. It uses a Merkle tree to verify integrity of the files and stores its root hash in the so-called tag of the file system. Any change of a file will result in a new tag, hence attempts to modify the content of the file system or to roll back to an older version can be detected by comparing the expected tag with the actual tag of the file system. PALÆMON ensures that there is no violation of integrity or freshness by verifying the value of tag on each file system access.

In order to prevent rollback attacks, it is critical to keep the expected tag value up-to-date. This value is kept inside of a TEE but is lost upon crash or when the application terminates (see Fig. 5). Our approach is to persist the expected tag: each time (i) a file is closed; (ii) the file system is synchronised; (iii) or the application exits, the runtime system pushes the expected tag to PALÆMON via the TLS connection that was established during application startup to perform attestation. PALÆMON stores the expected values in its database. As these values are essential for protecting the integrity and freshness of files, the expected tags must themselves

\footnote{In reality, PALÆMON can associate an application with multiple tags to simplify the mapping of encrypted volumes into containers.}
be protected against rollback attacks. We show in §IV how PALEMON efficiently protects its database against rollbacks.

A policy can also define a strict mode for an application. In that case, PALÆMON only permits a restart of the application if the expected tag was properly sent upon exit during the last execution of the application. Otherwise, the restart requires an explicit update of the policy, which is needed to adjust the tag and must in turn be approved by the policy board.

E. Secure Update

PALÆMON protects the CIF of both code and data. The binary code that is initially loaded in the TEE is just integrity- and freshness-protected since we can only get secrets after the initial attestation of the code. In contrast, all code that is loaded after the start of the TEE is CIF-protected. For example, an application can load dynamic libraries in main memory, with these being transparently decrypted and CIF-protected by PALEMON. Code that is loaded by interpreters and just-in-time engines is CIF-protected in the same way.

Along the same lines, PALEMON can also perform secure software updates of an application with the help of a policy update. Applications are typically packaged in a container image and data (e.g., a database) is mapped into the container via a volume. A new version of the code results in a new MRE and tag of the container file system. The new MRE and tag must be updated within the security policy to permit the new version to start, and this update must be approved by the policy board.

Consider the example of an image provider who maintains an image that is regularly updated, for example a Python interpreter running inside of a TEE. As software is updated, old versions of the image should be disabled and new versions enabled. To reduce the effort for applications that build upon this image, the provider will create a security policy defining in our example the MRE for the Python interpreter and a tag covering all the dynamic and Python libraries. This information is exported, and can then be imported by other security policies. Any application that uses the original image can use the exported information in its own security policy. Additionally, the application’s policy can limit the permitted combination of MREs and tags, e.g., only allow combinations that were checked by an external service. The application will only run with combinations that are permitted by both the image’s and the application’s policies. The advantage of computing this intersection is that, if the image provider removes a combination that has become unsafe, e.g., after discovering a vulnerability, the combination will be automatically disallowed by the application’s policy as well.

IV. IMPLEMENTATION

In this section, we describe how to address some of the challenges we faced when implementing our approach. Our implementation is based on the SCONE platform [5] running on top of Intel SGX [22]. However, note that PALÆMON is designed in a generic way that can be used not only for SCONE but also for other SGX platforms such as Graphene. We selected SCONE since it is easy to use compared to other platforms. To run an application with Intel SGX, we just need to compile its source code with the SCONE compiler, or just link the binary of the application with the SCONE libc.

We also considered ARM’s TrustZone TEE [4], but it only supports a single secure zone rather than multiple enclaves and it lacks an attestation protocol. Meanwhile, the current version of AMD’s TEE, SME/SEV, lacks integrity protection and is vulnerable to server-side rollback attacks [54], [36], [25]. PALÆMON runs inside a TEE, i.e., inside an SGX enclave. It is implemented in Rust [52] to ensure strong type safety. We use an encrypted embedded SQLite [1] database running inside the same enclave as PALÆMON. We describe below how this database is protected against rollbacks without introducing any major performance bottlenecks.

A. Application Attestation and Configuration

Upon startup, an application is transparently linked with the SCONE runtime and loaded inside a TEE. The runtime first attests the application with the help of PALÆMON before passing control to the application. To do so, it creates a random key pair and gets a report from a local quoting enclave [42] that associates the public key with its MRE. The runtime sends the report via a newly-established TLS connection to PALEMON and passes along the name of its security policy which is stored in an unprotected environment variable. The PALEMON instance verifies that: (i) the public key of the TLS client certificate matches the public key of the report; (ii) the security policy name exists and the MRE is valid for the application; and (iii) the application runs on a permitted platform—which we can verify with the report. If this attestation succeeds, PALEMON sends the following data to the application: the command line arguments; the environment variables; the keys and tags for the file system; and the set of files in which secrets should be injected together with the secrets as key/value pairs.

The PALEMON runtime supports transparent injection of secrets into existing configuration files via a simple variable replacement mechanism. This allows us to inject different secrets into different instances of the same application image, without the need to change the source code. Like all files, they can be CIF-protected via transparent encryption by the PALEMON runtime. The runtime injects the secrets it received from the PALEMON instance in each file as follows. The file is first read in TEE memory, then parsed, and all variables found are replaced by their values. Whenever the file is accessed, it is served from memory. While sizeable files can also be stored encrypted in main memory or on the file system, configuration files are typically small, so we keep them in TEE memory as long as they fit.

B. PALEMON Attestation

A client of a managed PALEMON instance must be able to ensure that the code of PALEMON was not modified and indeed runs inside of a TEE. As a matter of fact, we must guarantee that an infrastructure provider cannot configure PALEMON in any way that breaks the trust given by the client in PALEMON. We enforce this by designing PALEMON for its behaviour to depend solely on MREs. Thus, PALEMON has zero configuration parameters that affect its behaviour with regard to ensuring the CIF of the data stored in the instance by the clients.

A client connecting to a PALEMON instance has to attest the instance before performing any action, such as creating a new security policy. During the initial startup, a PALEMON instance creates a unique public/private key pair, as well as a random key to encrypt its file system, and stores these keys in sealed storage [37]. During a restart (after an exit or a failure), the instance reads the keys from sealed storage to be able to
We therefore adopt an alternative approach based on the observation that PALEMON runs on well-maintained hosts that have very limited unscheduled downtimes. For example, there would typically be an uninterruptible power supply (UPS) system to reduce the likelihood of power outages. For any unscheduled outage, we expect that we need to perform a fail-over to another PALEMON service instance anyhow. In our approach, illustrated in Fig. 6, we protect against rollbacks using a version number \( v \) stored in PALEMON's encrypted database and a hardware-based monotonic counter \( c \) that keeps track of this version number. Upon startup, PALEMON checks that the monotonic counter \( c \) and the version \( v \) of the database match, i.e., \( v = c \), and otherwise exits. PALEMON then increments the monotonic counter before accepting any request. The database is now trailing the monotonic counter, i.e., \( v < c \). This will prevent any further restarts unless PALEMON updates \( v \) during shutdown. Furthermore, PALEMON checks that the increment effectively yields \( c = v + 1 \).

Any higher value for \( c \) would indicate that a second instance is already running. In such a case, PALEMON would exit immediately. As common for containers, PALEMON is terminated via a signal. In that case, it shuts down all connections and stops accepting new requests. Existing requests are still processed and the internal database is updated. The final step is to increment the version in the database and shut down the service. In this way, the monotonic counter and the version of the database agree again, thus allowing PALEMON to restart.

Note that the monotonic counter \( c \) and the version \( v \) are not incremented for every update to the expected tag (see §III-D). Thus, our rollback protection mechanism can achieve significantly higher throughput and lower latency compared to previous approaches (see §V). However, in this work, we treat a systems crash as a case of attacks, i.e., we ensure the consistency and freshness with an assumption about availability. Ensuring both consistency and availability is a challenging task, which we currently address in our ongoing work.

### E. Policy Access Control

Security policies can be accessed via a REST API protected by TLS. Clients connecting to a PALEMON instance attest the instance by verifying that it has a certificate issued by the PALEMON CA. A client must also provide a client certificate, which is stored upon creation of the security policy. All further accesses (i.e., read, update, delete) to this policy are limited to the clients with the same certificate, and also require approval by the policy board. Multiple clients can easily share the same certificate by running as part of a single security policy.

### V. Evaluation

We evaluate PALEMON with respect to its security and its performance. First, we introduce a security analysis. Second, we measure the overheads both at the micro-level in controlled environments and at the macro-level in real deployments.

#### A. Security Analysis

In terms of secret management, PALEMON provides stronger security guarantees compared to previous systems like Barbican [60] or Vault [35]. PALEMON protects against eavesdropping on any communication by only supporting TLS-based communication using ciphers with perfect forward secrecy [33]. To avoid man-in-the-middle attacks by potentially
and tracking the freshness if not otherwise ensured—for all serves its IAS reports as a second way to be attested by its policy, and a security policy can only be modified when an secrets. Access rules are defined and enforced per security and data outside the TEE are always encrypted. Hence, even by executing securely inside a TEE. All communication, files object storage like PESOS [45].

by the use of a trusted and durability of the storage backend a monotonic counter); and

file (protection against rollbacks is ensured with the help of a Merkle tree of its files and storing this hash value in a sealed control of its storage backend.

A P A LÆMON instance is protected against some types protect against authorized but Byzantine client accesses. Access to security policies is controlled with the help of certificates. Each client has to be authorized to access a security policy: a client must know the private key that corresponds to the public key used to create the security policy. Note that no other entity, like the provider managing the P A LÆMON instance, can access this policy without knowing this private key. Therefore, only the client that creates a security policy controls access to this security policy. Any policy access must additionally be authorized by its policy board to protect against authorized but Byzantine client accesses.

P A LÆMON protects the CIF of data by encrypting all data and tracking the freshness if not otherwise ensured—for all data at rest, in transit or in main memory. This requires us to effectively protect the secrets, such as the symmetric and/or asymmetric keys. P A LÆMON protects against unauthorized accesses to secrets by enforcing the following: (i) secrets are defined in the context of a security policy; (ii) each application runs in the context of a single security policy; (iii) only applications running in the context of a security policy are permitted to retrieve secrets of this security policy; the security policy specifies for each of its applications secrets it is permitted to access; and (iv) both the application code and its file system state are specified in the security policy and attested before the application can gain access to any secrets.

Access to security policies is controlled with the help of certificates. Each client has to be authorized to access a security policy: a client must know the private key that corresponds to the public key used to create the security policy. Note that no other entity, like the provider managing the P A LÆMON instance, can access this policy without knowing this private key. Therefore, only the client that creates a security policy controls access to this security policy. Any policy access must additionally be authorized by its policy board to protect against authorized but Byzantine client accesses.

P A LÆMON protects the confidentiality of stored secrets by encrypting all secrets at rest with a randomly selected key only known to itself. By always executing inside of a TEE, P A LÆMON protects against memory analysis of a running instance. A P A LÆMON instance is protected against some types of control of its storage backend by providing: (i) protection against manipulation (including rollbacks), by maintaining a Merkle tree of its files and storing this hash value in a sealed file (protection against rollbacks is ensured with the help of a monotonic counter); and (ii) protection of the availability and durability of the storage backend by the use of a trusted object storage like PESOS [45].

P A LÆMON protects against attackers with superuser access by executing securely inside a TEE. All communication, files and data outside the TEE are always encrypted. Hence, even users with superuser privileges cannot access or modify any secrets. Access rules are defined and enforced per security policy, and a security policy can only be modified when an authorized client requests a change that must then be approved by the policy board of the security policy.

Although side-channel attacks are out of scope of this work, it is worth to mention that the underlying SCONE platform can protect against L1-based side channels attacks [59] and is hardened against Iago attacks [19]. To mitigate the various variants of Spectre [44], we can use LLVM-extensions, e.g., speculative load hardening [15] that prevent exploitable speculation.

B. Micro-benchmarks

Evaluation Settings. All our experiments are executed on a rack-based cluster of Dell PowerEdge R330 servers. Each machine is equipped with an Intel Xeon E3-1270 v6 CPU and 64 GB of RAM. The machines are connected to a 20 Gb/s switched network. SGX is statically configured to reserve 128 MB of RAM for the enclave page cache (EPC) [22]. We use Ubuntu 16.04 LTS with Linux kernel v4.13.0-38. The CPUs use the latest microcode patch level.

The underlying SCONE runtime also supports emulation mode (EMU) to run legacy applications without any TEE support. We use EMU during the evaluation where indicated to highlight the performance overhead of the TEE.

Enclave Startup Times. First, we evaluate how long it takes to start an application inside an SGX enclave. P A LÆMON automatically loads an application inside of an enclave with the help of a modified loader. Setting up an enclave includes: (i) adding pages to the enclave; (ii) measuring their content; (iii) evicting pages if the enclave’s size exceeds the EPC; and (iv) bookkeeping tasks such as allocating memory and copying data. We measured the throughput of each component with a micro-benchmark (see Table II).

On new SGX-capable CPUs, the P A LÆMON runtime will dynamically allocate heap memory, i.e., startup times are mainly determined by the time it takes to load the code with some minimum heap. When the runtime fails to allocate memory, it tries to add new heap pages to the enclave. Current CPUs support SGX enclave sizes of up to 64 GB. This limit is expected to increase much further, i.e., we could run most applications inside of enclaves.

To ensure the integrity of an enclave, we need to measure all its code and initialized data segments. The internal memory allocator is aware of the position of the contiguous enclave memory. It will not use memory outside of the enclave, and it overwrites requested memory with zeros, avoiding measurement of added heap pages. For small initial enclaves—which we expect to be common when adding heap memory dynamically—bookkeeping and page addition times are typically the dominant factors, despite the slow measuring speed (see Fig. 7).

Attestation and Configuration. First, we evaluate how long it takes to attest and configure an application. The advantage of P A LÆMON over the traditional way using IAS to perform attestation is that P A LÆMON runs on the local cluster. We measured the time it takes to perform the individual steps of remote attestation (§IV-B). The IAS experiment ran on servers in Europe and in Portland, OR, USA (close to IAS servers). In the future, we will support both IAS and DCAP [66]. PA LÆMON’s attestation infrastructure will stay the same, as it attests other factors like the file system state.
Table II: The average throughput of measuring pages is about an order of magnitude slower than evicting or adding pages.

| Bookkeeping | Eviction | Measurement | Addition |
|-------------|----------|-------------|----------|
| 1,292 MB/s  | 1,219 MB/s | 148 MB/s    | 2,853 MB/s |

Fig. 8: Attestation and configuration latencies: even when located close to Intel’s IAS server, attestation with IAS takes an order of magnitude longer than with PALÆMON.

Fig. 8 shows the time it takes to: (i) initialize the necessary resources; (ii) send the quote to PALÆMON; (iii) wait for PALÆMON to confirm the successful attestation; and (iv) receive the configuration. The initialization phase includes key pair generation, DNS resolution, connection establishment, and TLS handshake with PALÆMON. Overall, the initialization time is similar for each attestation service and is dominated by the TLS handshake.

Obtaining and sending the quote takes longer for IAS variants for two reasons. First, performing IAS attestation requires providing information that is embedded into the generated quote, which adds one round trip. Second, PALÆMON attestation cryptography (Ed25519 [8]) is less expensive than the one used by IAS (EPID [13]). However, the dominating factor for IAS is the time spent waiting for the attestation. PALÆMON has to verify the quote either by querying the IAS or by verifying the signature and looking up the public key of the quoting enclave [22] (QE). Overall, PALÆMON attestation takes around 15 ms to complete, which is an order of magnitude faster than IAS attestation which takes 280 ms when performed from the USA, or 295 ms from Europe.

PALÆMON also decouples application startup from IAS. Our benchmark starts multiple minimal programs in parallel to measure the startup throughput and latency. Fig. 9 depicts the latency and throughput for different attestation variants. In the Native case (SGX and attestation are not involved), the throughput scales well until all eight hyper-threads are fully utilized. At this point, the system runs around 3,700 programs every second. If the program is compiled with SGX but without attestation (SGX w/o), the throughput drops to about 100 executions per second. This variant does not scale well with increasing parallelism. We tracked down the bottleneck to the Intel SGX driver synchronising EPC page (de)allocations with a single lock. Since every enclave has to obtain EPC pages at roughly the same time, this lock basically enforces page requests to be served sequentially.

With IAS and PALÆMON, the startup routine performs remote attestation before executing the actual program. With PALÆMON attestation, we quickly reach the maximal achievable start rate of about 90 runs per second. IAS attestation needs a considerable amount of parallelism to partially hide the higher latency, reaching about 40 runs per second (60 parallel instances) at 1.4 s latency.

**Rollback Protection.** PALÆMON protects against rollback attacks by ensuring that the root tags of all volumes of a process are sent to PALÆMON on each file system synchronisation, file closing, as well as on program exits. PALÆMON stores the tags in its encrypted database. We measure the latency of the PALÆMON runtime reading and updating the most recent tag in the PALÆMON service to evaluate the overhead of rollback protection (Fig. 11 left). The update latency is roughly 6 × higher than the read latency, as the PALÆMON service database needs to be committed to disk for updates but not for reads.

PALÆMON itself is protected against rollbacks with the help of a monotonic counter. To that end, we use the monotonic counters [17] provided by the SGX platform. Independent measurements have shown that these counters allow between 4 [51] and 17 [10] increments per second. TPM-based counters have a throughput of approximately 10 increments per second and wear out after 300 k to 1.4 M writes [68]. The ROTE system [51] stores the monotonic counters in memory of a group of servers, achieving a throughput of about 500 operations per second with 4 servers in a local area network. However, the protection of ROTE against rollbacks is considered to be less robust than when using the platform counters. In contrast, the anti-rollback protection offered by PALÆMON in strict mode is as safe as the underlying monotonic counters, i.e., PALÆMON and its applications can only be rolled back if an attacker can roll back the monotonic counters of the platform.

We measure how fast we can increment a monotonic counter in the following scenarios (see Fig. 10): (a) using counters provided by the underlying platform and the Intel SGX SDK; (b) by opening a file, incrementing the integer stored in the file, writing back the new counter value and closing the file upon exit, when running in native mode; (c) like (b) but running inside SGX enclaves without encrypting the file; (d) like (c) but encrypting the file transparently with PALÆMON; and (e) like (d) but also updating the tags with PALÆMON by running in strict mode, i.e., the file is protected against rollbacks. Applications using PALÆMON often do not need to use monotonic counters since files are rollback-protected. Still, they sometimes use them to track for instance the number of executions.

Using the platform’s monotonic counters, we reach only 13
increments per seconds. Note also that this approach requires applications to be rewritten in order to be protected against replay attacks. Variant (b) shows that we can reach a much higher throughput of 682 k increments per second when using a simple file-based counter. When running inside of enclaves, throughput increases as files are transparently memory-mapped by the SCONE runtime to counter SGX overhead. When encrypting files, PALÆMON automatically performs caching, increasing the throughput even more. Sending the updated tag to a PALÆMON instance only slightly reduces the throughput. Our measurements show that applications could use a file-based counter and achieve throughputs that are 5 orders of magnitude higher than using the counters provided by the platform. This approach relies on our assumption that system crashes are considered attacks.

Secret Injection Latency. We measure the impact of injecting secrets in a file by an application running inside an enclave. To that end, we read a 4 kB file in which we inject 1 and 10 secrets (Fig. 11 right). We show the latency as well as the overhead compared to the baseline on top of each bar. PALÆMON achieves better latencies for files with injected secrets—even compared to the plain file baseline—because the secrets are injected during startup and stay in enclave memory.

Secret Access Latency. PALÆMON supports the retrieval of keys from remote PALÆMON services. We measure the overhead of retrieving local and remote secrets, i.e., when using PALÆMON in a decentralized fashion (Fig. 12). There is no visible increase in latency when retrieving 1, 5, 50 and 100 keys of 32 bytes. As a matter of fact, retrieving 50 or 100 keys consistently outperforms 1 or 5 keys. However, there is an impact if a peer service is located on a different continent instead of the same data centre. This is mainly caused by the time it takes to establish of a TLS connection.

Approval Service. We measure the performance of the approval service running inside a TEE and compare it against a native version. In both variants, we consider HTTP connections with and without TLS to show its impact. The approval service and the client issuing requests run on the same rack. We show the measured throughput/latency plots for these four combinations in Fig. 13 (left). In these experiments, we issue approval requests at fixed rates (achieved throughput against a native version. In both variants, we consider HTTP

Fig. 11: Left: latency of PALÆMON tag reads and updates. Right: reading overhead for a file with 1 or 10 secrets normalized by the time to read a plain file.

Fig. 12: Latency to retrieve multiple secrets (up to 100) from a PALÆMON service deployed locally, from the same data centre (DC) or from an instance running on a different continent.

Fig. 13: PALÆMON’s approval service: throughput/latency (left) and response latency (left) for different geographical deployments (from local to intercontinental).

Fig. 14: Barbican. Throughput/latency of several variants (native, PALÆMON and Barbie [18]) with two different microcodes.

approval service running inside a TEE and compare it against a native version. In both variants, we consider HTTP connections with and without TLS to show its impact. The approval service and the client issuing requests run on the same rack. We show the measured throughput/latency plots for these four combinations in Fig. 13 (left). In these experiments, we issue approval requests at fixed rates (achieved throughput against a native version. In both variants, we consider HTTP
with pre-Spectre (version 0x58) as well as post-Foreshadow microcodes (0x8b). PALÆMON exhibits some overhead since the arguments of system calls must be checked by the syscall shield while arguments are being copied out of the enclave and return values are copied back in. BarbIE performs better than Barbican native due to its small trusted computing base (TCB) and more efficient compiled code, rather than interpreted. Finally, the observed performance drop is of approximately 30% when using the newer microcode. We attribute this to the flushing of L1 cache on enclave exit, required to mitigate the L1TF vulnerability, as also reported by Intel [41] and Weichbrodt et al. [72]. BarbIE does not suffer as much since it requires less EPC paging and has a low number of enclave exits, in line with its number of requests per second.

**Vault.** We evaluate Vault (v0.8.1) compiled by gccgo in Alpine Linux (Fig. 15). We use wrk2 [69] to retrieve secrets from Vault by providing it with an appropriate token. Vault requires a heap of at least 1.9 GB to start, i.e., the enclave is much larger than the EPC, so paging takes place. Our evaluation shows for instance that, for latencies below 1 s, PALÆMON still achieves 61% of native throughput when running in hardware, and up to 82% when running in EMU mode.

**memcached.** We evaluate the impact of PALÆMON for running TLS protected memcached [27]. In particular, PALÆMON injects the certificates and private keys for TLS termination. We use memtier [63] to load and stress memcached. Fig. 16 shows the measured latency and throughput of the evaluated systems. We make a comparison between PALÆMON and native memcached using stunnel [74] TLS connections for both systems. With latencies smaller than 3 ms, PALÆMON achieves 59.5% and 65.3% of native throughput with hardware and EMU mode, respectively.

**NGINX.** Along the same lines, we use an encrypted NGINX [64] container image and rely on PALÆMON to: (i) encrypt all the files; (ii) inject the certificates; and (iii) inject private keys used by NGINX for TLS termination. The benchmark issues GET requests on 67 kB files (nowadays’ average size of an HTML web page [43]) with the wrk2 tool (see Fig. 17 (a)). We see that the overhead of SGX alone is less pronounced than that of encrypting all files. Tuning the caching done by NGINX could improve the performance when encrypting files. There is little difference between running in emulation mode and inside of an SGX enclave, since not much paging is taking place.

**ZooKeeper.** Next, we evaluate the overhead of PALÆMON with the ZooKeeper coordination service. We deploy a cluster of three nodes and evaluate three ZooKeeper variants: (i) native using stunnel [74] for TLS termination between servers; (ii) shielded ZooKeeper running together with the JVM in hardware mode; and (iii) EMU mode. We use the ZooKeeper Benchmark [48] to measure read and write throughput. The read throughput of the shielded versions is consistently better than the native one (Fig. 17 (b)). The write throughput (Fig. 17 (c)) exhibits better performances in native mode, as it involves the execution of consensus [39] via TLS, resulting in more code and system calls being executed. Our results are on par with SecureKeeper [12], despite its use of an encryption proxy to protect the content only.

**MariaDB.** We conclude our macro-benchmarks by measuring the throughput of MariaDB configured to perform encryption at rest [49]. We use PALÆMON to inject a generated X.509 certificate, the private key and the encryption key. We execute the TPC-C benchmark [70] and vary the available buffer cache. Fig. 17 (d) presents experimental results. For small buffer pool sizes [61], i.e., <128 MB, all configurations behave similarly since the main overhead is hardware I/O. For larger buffer caches, EPC paging increases in hardware mode. Hence, adding more buffer cache reduces the throughput while it increases the throughput in emulation and native mode. A fair comparison with the recently proposed EnclaveDB [62] system is currently not possible since it lacks paging support and its performance figures are only based on simulations.

**VI. PRODUCTION USE CASE**

Finally, we describe a deployment of PALÆMON in a real production environment for a company offering an online service for automatic conversion of handwritten documents into digital data via machine learning. Typically, customers of this company want to acquire inference results and, due to the sensitive nature of the documents, ensure the confidentiality of the input images. Additionally, the company wants to protect both the inference engine (implemented in Python) and its machine learning models.

To achieve these security goals, the company has deployed PALÆMON as follows. First, the company relies on SCONÉ’s file system shields [5] to encrypt Python code and models used for the inference. The customers use the same mechanism to encrypt the input images. However, the company and the customers do not share with each other the keys and tags to decrypt and ensure the freshness of their digital assets. Instead, they define a dedicate security policy to define the access control to those. Thereafter, they submit the policy to PALÆMON after performing the attestation (see § IV-B) to ensure code integrity. To process an image, it takes on average 323 ms and 1202 ms (3.7× slowdown) with the native and the PALÆMON-enabled
version, respectively. However, the result is less than 1.5 seconds and thus considered acceptable in a production setting.

VII. RELATED WORK

Key management systems (KMSs) [60], [55], [35] provide an integrated approach for generating, managing and distributing cryptographic keys for devices and applications. They are at the core of secure distributed systems and have been widely studied. Many approaches rely on cryptographic techniques, often embedded in secure hardware modules [58], [57]. There are also alternative ways for securing secrets by mixing Byzantine replication and cryptography [50], [9], [6]. However, they imply the costs of replication and solve only part of the problem we are addressing with PALÆMON.

Recent cloud computing frameworks integrate dedicated services for key management. Barbican [60] and Vault [35] are popular standalone KMSs. Both rely on the operating system (OS) for security, and thus consider a weaker threat model than PALÆMON which considers attackers with superuser access (see §II-A). Barbican and Vault can be protected against such attackers by running them on top of PALÆMON; we evaluate these hardened variants in §V. Several major cloud providers also offer managed services to create and control encryption keys, e.g., Amazon [2], Google [31] and Microsoft [53]. Users must trust the providers to protect their secrets while PALÆMON can be both managed by a provider and attested by users to establish trust in it.

While previous KMSs integrate hardware security modules (HSMs) to provide better protection, we deem this approach vulnerable to the adversary PALÆMON protects against. An adversary with superuser access can eavesdrop on the HSM to obtain secrets, or directly hijack the KMS and observe the secrets distributed to clients.

To the best of our knowledge, while TEEs have been widely used to secure many applications, only two systems are using TEEs to harden a KMS against adversaries with superuser privileges. Researchers from Intel proposed the use of SGX for securing Barbican [18]. Along the same lines, Fortanix’ self-defending key management service (SDKMS) [46], [7] also uses SGX to securely generate, store and use cryptographic keys, certificates and various types of secrets. Both approaches essentially provide a replacement for the functionality normally provided by HSMs by using enclaves, hence reducing costs and providing better extensibility. Like classical HSMs, they still need passwords or personal identification numbers (PINs) in configuration files to authenticate clients. In contrast, PALÆMON provides an integrated approach to free itself from such sensitive identifiers and use the application code itself for authentication and authorization. PALÆMON also provides several additional features not found in other systems, e.g., advanced governance by a policy board, secret sharing between service instances and rollback protection.

To integrate KMSs into legacy applications without changing their source code, systems as Vault [35] process configuration files and environment variables using scripts (e.g., consul-template and envconsul) before executing the application [23]. However, since this environment is maintained by the OS, it is thus accessible to attackers with superuser privileges. Hence, this is not a viable solution to protect against privileged attackers. PALÆMON provides transparency by establishing the environment expected by the application inside the TEE, hence never exposing its secrets to the OS.

We finally mention that secrets are sometimes stored in configuration management services Chubby [14], Consul [34], ZooKeeper [39] (or its SGX version SecureKeeper [12]) along with other configuration data. Note that ZooKeeper neither encrypts data on disk nor does it protect its network communication. With PALÆMON, we can retrofit the necessary features to protect ZooKeeper in a cloud context (see §V).

VIII. CONCLUSION

We introduced PALÆMON, a service to manage trust in untrusted environments with Byzantine stakeholders. Unlike in the Byzantine Fault Tolerance [16] approach, we can enforce—via remote attestation—that the correct application code is executed. In this way, we do not need to deploy multiple replicas to enforce integrity and freshness. Moreover, we also enforce confidentiality. In order to support application updates, the root of trust of an application is a group of stakeholders—some of which might be Byzantine. We protect applications with the help of TEEs: PALÆMON clients can securely create secrets and protect access to these secrets with a security policy, even from insiders and attackers with superuser access.

To avoid source code changes, PALÆMON passes the secrets to applications as arguments, environment variables and by transparently injecting these into files. Our evaluation indicates that applications can achieve good throughput despite running in TEEs. Throughput of our monotonic counters is 5 orders of magnitude higher than those offered by the SGX platform.

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