ReplicaTEE: Enabling Seamless Replication of SGX Enclaves in the Cloud

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Abstract—With the proliferation of Trusted Execution Environments (TEEs) such as Intel SGX, a number of cloud providers will soon introduce TEE capabilities within their offering (e.g., Microsoft Azure). Although the integration of SGX within the cloud considerably strengthens the threat model for cloud applications, the current model to deploy and provision enclaves prevents the cloud operator from adding or removing enclaves dynamically—thus preventing elasticity for TEE-based applications in the cloud.

In this paper, we propose ReplicaTEE, a solution that enables seamless provisioning and decommissioning of TEE-based applications in the cloud. ReplicaTEE leverages an SGX-based provisioning layer that interfaces with a Byzantine Fault-Tolerant storage service to securely orchestrate enclave replication in the cloud, without the active intervention of the application owner. Namely, in ReplicaTEE, the application owner entrusts application secret to the provisioning layer; the latter handles all enclave commissioning and decommissioning operations throughout the application lifetime. We analyze the security of ReplicaTEE and show that it is secure against attacks by a powerful adversary that can compromise a large fraction of the cloud infrastructure. We implement a prototype of ReplicaTEE in a realistic cloud environment and evaluate its performance. ReplicaTEE moderately increments the TCB by \( \approx 800 \) LoC. Our evaluation shows that ReplicaTEE does not add significant overhead to existing SGX-based applications.

I. INTRODUCTION

In the last few years, the cloud has been gaining several adopters among SMEs and large businesses that are mainly interested in minimizing the costs of deployment, management, and maintenance of their computing infrastructure. Cost effectiveness is realized in the cloud by coupling multi-tenancy with tailored distributed algorithms that ensure unprecedented levels of scalability and elasticity at low costs [7].

With the recent proliferation of Trusted Execution Environments (TEEs) such as Intel SGX, a number of cloud providers will soon introduce TEE capabilities within their offering (e.g., Microsoft Azure [2]). The embedding of TEEs within the cloud allows the design of secure applications that can tolerate malware and system vulnerabilities, as application-specific secrets are shielded from any privileged code on the same host. As such, SGX has fueled innovation in the area of secure computation, with an increasing number of proposals that promote TEE-based applications in the cloud [24], [32], [31].

Although the integration of SGX within the cloud considerably strengthens the threat model for cloud applications, the current model to deploy and provision an enclave, prevents the cloud operator from adding or removing enclaves dynamically—thus effectively hampering elasticity for TEE-based applications in the cloud. Namely, SGX enclaves bear no secrets when deployed; secrets are securely provisioned to the enclave by the application owner (also known as Independent Software Vendor or ISV) after he attests the application code and makes sure that it runs untrammed in an enclave on an SGX-enabled platform. In a nutshell, dynamic enclave allocation for TEE-based applications in the cloud requires the ISV to be online throughout the whole application lifetime. The only alternative for an ISV is to entrust the secrets of his application to the cloud provider (in a way similar to the provisioning of Virtual Machine images that carry secret material). This, however, obviates the shift to deploy SGX enclaves in the cloud since it exposes all application secrets to malware that may potentially penetrate the cloud infrastructure.

Although the community features a number of studies on SGX security in the cloud [29], [12], [13], no previous work has addressed the problem of enabling seamless provisioning and decommissioning of enclaves in the cloud. Here, there are a number of challenges to overcome. One the one hand, such a service should remove the need of an online ISV. On the other hand, it should warrant ISVs the same security provisions of the current deployment and provisioning models, where ISVs attest and provision secret material to their applications. Furthermore, unrestricted enclave replication in the cloud may amplify the effectiveness of forking attacks for application that keep persistent state [12]. In a forking attack, the adversary runs several instances of an application and provides them with different state or inputs in order to influence their behavior. For example, consider an authentication service running in SGX enclaves. To mitigate brute-force attacks, the service may use rate-limiting and, for example, allow up to 3 password trials per account. An adversary that manages to compromise the cloud infrastructure could launch several instances of the service in order to increase the number of trials per account and brute-force passwords. A service that automatically provisions enclaves must, therefore, control the number of running enclaves for...
a given application at all times, despite potential malware that may penetrate the cloud infrastructure.

In this paper, we propose ReplicaTEE, a solution that enables dynamic enclave replication and de-commissioning for TEE-based applications in the cloud. ReplicaTEE leverages a distributed SGX-based service layer that interfaces with a Byzantine Fault-Tolerant (BFT) storage layer to orchestrate secure and dynamic enclave replication in the cloud. Namely, in ReplicaTEE, the ISV entrusts application secrets to the service layer and can go offline. The service layer is a thin software layer that runs in SGX and handles commissioning and de-commissioning of enclave replicas on behalf of the ISV. Application secrets are, therefore, shielded away from malware that penetrates the cloud, as they are securely transferred from the ISV to the service layer onto application enclaves. The service layer also controls the number of running replicas for a given application, in order to mitigate forking attacks against victim applications. Finally, in order to prevent forking attacks to the service layer itself, ReplicaTEE uses a distributed BFT storage layer that guarantees dependable storage despite compromise of a fraction of its nodes.

We design ReplicaTEE to be fully compliant with the existing Intel SGX SDK. We analyze the security of ReplicaTEE and show that it enables secure enclave provisioning and decommissioning even in presence of a powerful adversary that compromises a large fraction of the cloud infrastructure. We also implement a prototype of ReplicaTEE in a realistic cloud environment and evaluate its performance. Our evaluation shows that ReplicaTEE only moderately increments the TCB by approximately 800 Lines of Code (LoC) and does not add significant overhead to existing SGX-based applications.

The remainder of this paper is structured as follows. In Section II, we review Intel SGX and BFT storage solutions that leverage TEEs. In Section III, we introduce our system and threat models, we discuss our design goals and provide a brief overview of our solution. In Section IV, we present ReplicaTEE and analyze its security. In Section V, we evaluate a prototype implementation based on the integration of ReplicaTEE with a realistic cloud environment. In Section VI, we review related work in the area, and we conclude the paper in Section VII.

II. PRELIMINARIES

In this section, we briefly overview the main operations of Intel SGX and we outline existing Byzantine Fault-Tolerant storage protocols that leverage TEEs.

A. Intel SGX

Software Guard Extensions (SGX) is the latest realization of Trusted Execution Environment (TEE) by Intel, available on Skylake and later CPUs. It allows application to run in secure containers called enclaves with dedicated memory regions that are secured with on-chip memory encryption. Access to the encrypted memory is mediated by the hardware, effectively excluding the OS or any other software from the Trusted Computing Base (TCB).

Privileged code on the planform can create and add data to an enclave with instructions ECREATE, EADD, EINIT. After creation, the enclave code can only be invoked using a thin interface via instructions ENTER and ERESUME; enclave code returns by calling EEXIT, which ensures that any sensitive information is flushed before control is given back to the OS.

State persistence across reboots is available through sealing, i.e., hardware-managed authenticated and confidential persistent storage. Enclaves can use instructions EREPORT and EGETKEY to retrieve an enclave-specific (and platform-specific) key to encrypt data before writing it on persistent storage. Keys are uniquely bound to the identity of an enclave so that no other software including no other enclave can access them. Note that the sealing functionality that offers SGX does not ensure freshness. That is, a malicious OS may present stale state information to an enclave, what is commonly referred to as a rollback attack. This is in part mitigated by the use of monotonic counters provided by the platform. However, monotonic counters are apparently slow and the registries where they are stored wear out with usage.

SGX allows a remote party to verify that a piece of code runs in an enclave on an SGX-enabled platform. This mechanisms, called remote attestation, uses a Direct Anonymous Attestation (DAA) scheme that provides platform anonymity, i.e., the verifier is assured that the enclave runs on an SGX platform without being able to tell it apart from other SGX platforms. Remote attestation in SGX is a two-step process. During the first step, the enclave to be attested proves its identity to a system enclave present on every platform and called quoting enclave. The latter has access to the DAA signing key and produces a publicly verifiable quote that allows the verifier to remotely attest the enclave. In its current implementation, attestation involves an Intel service (Intel Attestation Service, IAS) that mediates communication between quoting enclaves and remote verifiers. In particular, the IAS only allows registered parties to issue remote attestation requests. Also, the quote produced by a quoting enclave is encrypted under the IAS public key, so that only the IAS can proceed with the verification. The IAS then signs a publicly verifiable statement to confirm that the enclave runs on an SGX platform. As a by-product of the attestation protocol, the prover and the verifier establish a mutually authenticated Diffie-Hellman key. In particular, the verifier signs its ephemeral key and the enclave must hold the corresponding verification key to verify the signature. Also, the quoting enclave (and IAS) guarantee that the proper ephemeral key belongs to that specific enclave running on an SGX platform.

B. Byzantine Fault-Tolerant Storage using TEEs

The community features a large number of Byzantine Fault-Tolerant protocols (BFT) based on state replication across different nodes, called "replicas". Some replicas may be faulty and their failure mode can be either

1Keys may also be bound to a “sealing authority” in order to allow secure storage across different versions of the same application.
crash or Byzantine (i.e., deviating arbitrarily from the protocol [28]). Classical BFT protocols require $3f + 1$ nodes and $O(n^2)$ communication rounds among these nodes in order to tolerate up to $f$ Byzantine nodes.

Since agreement in classical BFT is rather expensive, prior work has attempted to improve performance by leveraging trusted hardware. Namely, previous work showed how to use trusted hardware to reduce the number of replicas and/or communication rounds for BFT protocols [10], [23], [33]. For example, MinBFT [34] is an efficient BFT protocol that reduces the communication rounds and the number of replicas used by conventional BFT protocols, by leveraging functionality from TEEs, such as Intel SGX. As a result, the number of required replicas is reduced from $3f + 1$ to $2f + 1$. In MinBFT writers send write requests (e.g., using a PUT interface) to the replicas, which are all expected to execute the requests in the same order (i.e., maintain a common state). Readers can read content previously written onto the replica nodes. The main idea of MinBFT is to rely on the sequential monotonic counter provided by trusted hardware, in order to bind each message sent to a unique counter value. This is ensured by requiring a signature from the local TEE on all messages sent by the replica; the intuition is that the TEE will sign messages with a given counter value only once, thereby preventing replicas from assigning the same counter value to different messages—commonly referred to as equivocation. More details about MinBFT can be found in Appendix A.

III. Model & Overview

In this section, we introduce our solution, ReplicaTEE, which enables seamless replication of TEE-based applications in the cloud. We start by describing our system and threat model.

A. System Model

We consider a scenario where a cloud provider manages a set of Intel SGX-enabled platforms. Application owners, also known as Independent Software Vendors (ISV), can upload code to be executed on such platforms. Applications could either run computation on behalf of the ISV such as a map-reduce service [31], or provide public functionalities such as an online password-strengthening service [21].

Deployment. In a real-world deployment of ReplicaTEE, application owners would acquire (e.g., rent) VMs at the cloud and split the logic of their applications (e.g., by using available tools [27]) in sensitive code to be run in an enclave and non-sensitive code that can run inside the VM. Therefore, each of the cloud platforms would host VMs from different tenants and each VM would have one or more enclaves. However, for the sake of simplicity, we assume in this paper that the entire application code is executed in enclaves. Given this assumption, each of the cloud platforms hosts multiple enclaves belonging to different ISVs.

Dynamic Provisioning. Conforming with current elastic cloud settings, we assume that multiple instances of the same application enclave may dynamically be started or shut down. In the following, we use the term application enclave to refer to an instance of application code running in an enclave, and we use application to denote the logical entity spanning multiple enclaves running the same code.

We are agnostic on how the decision to add or remove application enclaves for a given application is made. For example, this decision may be taken by the cloud for reasons such as load, throughput, or efficient resource utilization. Alternatively, the application itself may monitor its performance and, when needed, ask the cloud to add or remove instances. Nevertheless, we assume that the ISV defines a deployment policy that includes an upper bound to the number of application enclaves that can run simultaneously. This is needed to mitigate forking attacks and ReplicaTEE must ensure that the ISV deployment policy is fulfilled at all times.

Storage. ReplicaTEE leverages a Byzantine fault tolerant storage instantiation based on MinBFT [34]. We opt to rely on MinBFT owing to its small code base. We assume a Key-Value storage abstraction [25] which exports two operations: PUT($k, v$), which stores value $v$ indexed by key $k$, and GET($k$), which returns the stored value indexed by key $k$. We assume that the default value for any key is a special value, which is not a valid value for a PUT operation. We also assume that PUT and GET operations can only be invoked by authorized clients.

BFT storage is primarily used to prevent forking attack against ReplicaTEE. Nevertheless, applications can also leverage the storage service to keep either immutable state (e.g., the private key of a TLS server [9]), and/or mutable state (e.g., a key-value store [13] that is read/written by all the application enclaves throughout their lifecycle). Indeed, secure storage offered by SGX (i.e., sealing) only allows for local storage and if several enclave applications require access to common storage, this must be provided as an additional service.

B. Threat Model

The goal of the adversary that we consider is twofold. On the one hand, the adversary may abuse the enclave provisioning process of ReplicaTEE in order to leak application secrets. On the other hand, the adversary may be interested in deploying a large number of application enclaves (i.e., larger than what is allowed by that application’s ISV) in order to amplify the effect of a forking attack against a victim application.

The adversary can compromise privileged code on a node and we denote that node as compromised. However, we include SGX in the TCB and therefore assume that the adversary cannot compromise SGX components (e.g., system or application enclaves) on the compromised node.

We allow the adversary to compromise any number of nodes that host application enclaves or cloud management services. However, we only allow the adversary to compromise up to $f$ out of $2f + 1$ nodes of the BFT storage

\footnote{The deployment policy may also define other constraints, e.g., number of enclaves running during day/night time, etc.}
layer. We argue that assuming a threshold to the storage nodes that an adversary can compromise is reasonable since compromising storage nodes (where no client-code can be deployed) is sensibly harder than compromising nodes where (malicious) clients can deploy their code. This assumption is in line with previous work on distributed BFT systems [21], [6], [28] and with previous work on forking attacks against TEEs [29]. Further, this assumption is unavoidable since no secure distributed storage is feasible when all storage nodes are compromised. Even if one would naively fit the entire logic of a storage node in an enclave, this leads to a large attack surface thereby weakening the assumption that enclave code is not susceptible of compromise. Splitting the logic between enclave and non-enclave code is the choice of all BFT protocols that leverage TEEs [21], [6], [28].

We also assume that the adversary controls the network and as such controls the scheduling of all transmitted messages. Finally, we do not consider DoS attacks and we do not take into account attacks specific to SGX, such as the ones that exploit side-channels [14]. We note that measures to mitigate attacks against SGX are orthogonal to ReplicaTEE and could be deployed alongside our solution.

C. Overview

To the best of our knowledge, there is no mechanism that enables enclave replication in a way that is transparent to the enclave owner. Clearly, a cloud provider can autonomously start an arbitrary number of enclaves as long as they do not require any secret material, nor do they need to access any confidential state information. However, as soon as an enclave requires a secret key (e.g., a TLS server such as Talos [9] or access to some confidential state (e.g., an encrypted key-value store such as SecureKeeper [15]), the enclave owner must be involved in the enclave startup process for attestation and secret provisioning.

Apart from the functional requirement of an online application owner, automatic enclave deployment in the cloud faces a number of security challenges. Namely, if deployment of application enclaves is mainly handled by the cloud, an adversary that manages to compromise the cloud infrastructure may try to run multiple enclaves of a given application, in order to mount forking attacks [12]. The enclave replication service must, therefore, be constantly aware of the number and status of deployed enclaves for a given application.

If we aim at designing an enclave provisioning service that removes the burden of being constantly online from the application owner, we should ensure that such service warrants its correct behavior to application owners and that confidentiality of the secrets is maintained in all the steps of the provisioning chain: from the application owner, until the target application. The security provisions of SGX make such a platform a promising candidate for the service we aim to design. If the provisioning service runs in an enclave, application owners can attest its code to ensure that the secrets of their applications will be handled properly. After attestation, an application owner can securely upload the secret key of its application and its MRENCLAVE to the provisioning service. From this moment on, the provisioning service acts on behalf of the application owner, by attesting enclaves of that application, ensuring that their untampered code runs in an enclave on an SGX-enabled platform, and by provisioning the application secrets. The provisioning service must also make sure that enclaves are deployed according to a policy set by the application owner, in order to mitigate forking attacks.

In our design, the provisioning service ensures that the ISV deployment policy is respected, but it does not decide when an enclave for a given application should be provisioned or decommissioned. The provisioning service should only assist the cloud when provisioning or decommissioning takes place. Namely, the decision to add or remove enclaves may involve business logic specific to the cloud provider. We separate our provisioning service from any business logic, so that the same service code may be used by several cloud providers. Furthermore, our design facilitates the use of open-source code that can be audited via remote attestation or publicly vetted.

We augment the cloud software stack with a layer named Enclave Management Layer (EML), dedicated to elastic enclave provisioning. EML is in charge of provisioning and decommissioning enclaves on behalf of application owners. EML is designed to run entirely in SGX so that (i) application owners can verify its code and (ii) sensitive data entrusted by application owners to EML is shielded by any other software running on the same host.

EML is distributed across enclaves and leverages a master-slave approach to ensure progress despite potential crashes. Since EML itself may be victim of forking attacks, we couple it with a BFT Storage Layer (BSL) that provides consistent storage despite Byzantine faults of a fraction of its nodes. EML uses BSL to maintain at all times a consistent view of the requests to provision/remove enclaves and the progress it has made to handle such requests. This design allows us to prevent forking attacks on EML while, at the same time, keeping the code-base of the provisioning service small enough to be run entirely in an enclave. Coupling a lightweight management layer such as EML and a BFT storage layer such as BSL, we enable the cloud to dynamically provisions enclaves to applications, while ensuring protection against forking attacks. Our solution is depicted in Figure 1. In a nutshell, application owners entrust the cloud provider with the application code, and EML with the secret material that the application needs to run (e.g., a secret key). When a new application enclave must be provisioned, EML acts on behalf of the application owner and ensures that (i) the deployment of the new enclave does not violate the policy defined by the application owner, (ii) the application code runs in an enclave on an SGX-enabled platform, and that (iii) the enclave is provisioned with the appropriate secret key, if required. When dealing with enclave decommissioning, we note that one cannot tell whether an enclave has been properly shut
Fig. 1: Sketch of ReplicaTEE system model. Independent Software Vendors (ISV) upload applications that may serve third-party users. The cloud monitors the load of applications and decides whether to add or remove enclaves for an application. This operation is carried out with the assistance of the Enclave Provisioning Layer (EML). The latter leverages the Byzantine Fault-Tolerant Storage Layer (BSL) that can be also used by applications.

down or whether its messages are being blocked. To solve this issue, each application enclave is granted a lease upon provisioning. That is, when EML provisions an application enclave, it also provides an “end-of-lease” timestamp. The application enclave should run until the lease expires, unless the lease is otherwise renewed.

IV. PROTOCOL SPECIFICATION

Before describing ReplicaTEE in detail, we start by outlining the process of remote proxied attestation which constitutes an essential building block that will be used in our solution.

A. Remote Attestation by Unregistered Verifiers

As mentioned in Section II, the Intel Attestation Service (IAS) controls that remote attestation is not abused by verifiers and, in particular, that SGX platforms are not tracked—which constitutes one of the main goals of Direct Anonymous Attestation [10]. Nevertheless, involving IAS as an intermediary in each remote attestation limits the adoption of this mechanism, especially by parties who are not registered with IAS. This limitation becomes especially relevant if the enclave runs a public service like a mail server. Indeed, it is rather unrealistic to assume that all users interested in setting up a mail account are registered to IAS; yet, users may want to attest the code of the mail server and ensure it runs in an enclave on an SGX-enabled platform.

In order to overcome this limitation and enable remote attestation with unregistered verifiers, we utilize a proxy registered to IAS. The proxy can be deployed by the cloud provider or by a third-party. Our proxied attestation protocol is depicted in Figure 2. There, we only provide an overview of the protocol; detailed message contents refer to the ones defined in the Intel SGX SDK Developer Reference [4]. Attestation via our proxy comes in two flavors, depending on whether the prover enclave “knows” (i.e., holds the public key of) the remote verifier. If the verifier is known to the prover, the proxy simply relays messages between prover and verifier; when the prover outputs and encrypted quote, the proxy (registered to IAS) forwards the ciphertext to IAS in order to get back the cleartext and provides the latter to the verifier. In case the verifier is unknown to the prover, the proxy also signs the ephemeral DH key chosen by the verifier. Therefore, the prover enclave must embed the public key of the proxy.

Our proxied attestation protocol allows any party to remotely attest an enclave and to establish an unilaterally or mutually authenticated DH key—depending on whether the identity of the verifier is known to the prover.

Note that our protocol is compliant with the standard attestation protocol that leverages the SDK provided by Intel for SGX and only require the enclave developer to include the public key of the proxy, in cases where attestation requests are expected from unknown verifiers.

B. ReplicaTEE Protocol Details

Setup. Recall that ReplicaTEE comprises two layers: a BFT storage layer named BSL and an enclave provisioning layer called EML. We assume that BSL is setup initially by the provider conforming with the setup of MinBFT [34]. The setup of EML unfolds as follows. The cloud provider C (or a third party) starts N enclaves, each running an instance of EML. The enclaves must attest each other and agree on a group key for secure group communication. For this task, we require each EML enclave to be aware of the identity of its peers (in order to attest them) and of the number N of enclaves that form EML. We use the group key exchange protocol by [17] and denote by
$k_{EML}$ the established group key. Note that attestation rules out active attacks. That is, SGX attestation ensures that only an instance of EML enclave running in an SGX environment can participate in the key agreement protocol. Once EML has been set up, the enclaves jointly generate a key-pair for a signature scheme and publish the verification key. Application owners must embed this key in their applications, in order to enable application enclaves to verify the legitimacy of the messages received from EML during attestation.

EML enclaves are organized in a Master-Slave approach. By default, the master enclave is the enclave that has the largest enclave identifier. During normal operation, the master is in charge of carrying out the main operations in EML while slaves simply assume a passive role.

EML's master implements a variant of the so-called “node guarding" protocol to keep track of the availability of the slaves; this essentially consists of the master exchanging alive messages with the slaves at regular intervals. The master enclave periodically sends a beacon request to the slaves to transmit information about their current state (e.g., stopped, active). If a slave does not respond to the request of the master within a certain timeout, the master considers the slave to be crashed and relays this information to the remaining slaves. On the other hand, the slaves also use this protocol to monitor availability of the master; if a request from the master is not received after a certain timeout, the slaves assume that the master itself has failed. In this case, the slave with the highest identifier from the set of active slaves, assumes the role of a master and starts issuing the beacon requests. This process ensures a continuous operation of EML in spite of potential crash failures. Needless to mention, this entire lightweight protocol runs within the enclaves of EML nodes. Further, if one of the EML nodes crashes, it can be restarted and it can recover its state (e.g., $k_{EML}$, EML node endpoints, etc.) from the BSL storage layer.

**Notation.** We denote an application and its binary by $\langle \alpha \rangle$ and $b_{\alpha}$, respectively. Also, $p_{\alpha}$ denotes the deployment policy defined by the application owner. In this paper, we assume the owner simply sets an upper bound to the number of enclaves that can run simultaneously. However, ReplicaTEE can be easily extended to account for more complex deployment policies.

EML assigns identifiers to applications and enclaves. An identifier for an enclave of application $\alpha$ looks like $eid = \alpha||mr_{\alpha}||h_{\alpha}$, where $mr_{\alpha}$ is the MRENCLAVE of the application, and $h_{\alpha}$ corresponds to the hash of the key established between EML and the enclave during attestation.

In order to keep track of applications and enclaves, EML leverages the storage functionality offered by BSL. In particular, for each application $\alpha$, EML keeps track of the following metadata:

1. $p_{\alpha}$: Upper bound to number of running enclaves.
2. $mr_{\alpha}$: MRENCLAVE.
3. $ak_{\alpha}$: Application secret key.
4. $enc_{\alpha}$: A list of tuples $(eid, key, st, eol)$ where $eid$ is an enclave identifier, $key$ is the key established between EML and the enclave during attestation, $st$ is a status variable, and $eol$ is the current end-of-lease timestamp for that enclave. Variable $st$ can take values in $\{att, run, tbd, tbs, sus\}$. An enclave has status “attested” (att) after being attested by EML. The status is changed to “running” (run) when the enclave is provisioned with the application secret key. The enclave status is set to “to be deleted” (tbd) or “to be suspended” (tbs) when the cloud requests the enclave to be deleted or suspended, respectively. Finally the status is set to “suspended” (sus) when the enclave has been suspended.

EML exports the identifiers of applications and enclaves to the cloud $C$ in order to efficiently manage enclaves for a given application. Note that application and enclave identifiers do not bear any sensitive information apart from the number of enclaves running for a given application—an information already available to the cloud.

We assume that the integrity and the confidentiality of data written/read to BSL (via PUT/GET) are protected by means of an authenticated encryption scheme. The key material for authenticated encryption is derived from the key shared by all EML enclaves, namely $k_{EML}$, by means of a key-derivation function.

We use application identifiers as the keys to the storage service and for each application we store a “flat” database to keep information of that application and its enclaves. In order to ease exposition, we slightly overload the PUT/GET interface as follows. We write $\text{Get}(\alpha; attr_{\alpha})$ to fetch only the value of attribute $attr_{\alpha}$ for application $\alpha$. Similarly, $\text{Put}(\alpha; attr_{\alpha} := value_{\alpha})$ sets $attr_{\alpha}$ to $value_{\alpha}$, leaving all other attributes at the same key unchanged. We also write $\text{Get}(\alpha; enc_{\alpha} : eid)$ to fetch only the enclave information related to $eid$ (i.e., $key$, $st$, $eol$) from the list $enc_{\alpha}$. Also, $\text{Put}(\alpha; enc_{\alpha} : (eid', key', st', eol'))$ writes to the list of enclaves $enc_{\alpha}$ of application $\alpha$ if $enc_{\alpha}$ already has a tuple with $eid == eid'$, this operation only updates the remaining fields to $key'$, $st'$, and $eol'$, respectively. If $enc_{\alpha}$ has no tuple with $eid == eid'$, then a new tuple $(eid', key', state', eol')$ is appended. We stress that this notation is only to improve the readability of our pseudocode. In reality, we always read and write the whole data associated to a given key.

**Attestation of EML Service and Initial Upload of Code.** Algorithm 1 lists the main steps carried out when an application owner wants to upload his application to the cloud. Before the application owner can entrust the management of his application to EML, he must verify the identity of the EML enclave and establish a secure channel. This is captured by the function $\text{PROXIED_ATTESTATION}($EML, $mr_{EML})$ that takes as input the endpoint of the enclave to be attested and the expected MRENCLAVE. The function returns the key established with the prover enclave, if attestation is successful; otherwise it signals an error by returning $\bot$.

Once the application owner has established a secure channel with EML, he uploads $p_{\alpha}$, $mr_{\alpha}$, $k_{\alpha}$ to EML and $b_{\alpha}$ to $C$. EML writes $p_{\alpha}$, $mr_{\alpha}$, $k_{\alpha}$, $\bot$ to BSL and sends an acknowledgement to the application owner. The cloud
Algorithm 1 Attestation of the EML Service and Initial Upload of Code

1: function AttestUpload
2:     k ← ProxiedAttestation(eEML, mrEML)
3:     if kα,EML == ⊥ then
4:         return -1
5:     end if
6:     Send (pα, mrα, kα) to eEML
7:     Send (bα) to C
8: end function

Algorithm 2 Deployment Request

1: function ProvisionRequest(α, e)
2:     mrα ← Get(α; mrα)
3:     kα,EML ← ProxiedAttestation(e, mrα)
4:     if kα,EML == ⊥ then
5:         return -1
6:     end if
7:     hα ← H(kα,EML)
8:     eid ← α||mrα||hα
9:     Put(α; encα : (eid, kα,EML, att, ⊥))
10: Send(ack, α, e, eid) to C
11: end function

stores bα and also sends an acknowledgement message to the application owner.

From this moment on, the application owner goes offline, while EML cooperates with C in order to increase or decrease the number of enclaves allocated to that application. C can, at any time, issue requests to EML to deploy or remove an enclave. Similarly, C can ask to suspend a running enclave or resume a previously suspended enclave. EML writes requests to storage in order to serialize them. Then, EML periodically reads from BSL in order to identify pending requests and dispatch them.

Deployment Request. At this stage, the cloud provider creates a new enclave e on an SGX platform and loads the code bα. It then contacts the EML enclave that is acting as master to trigger the attestation and provisioning of the enclave. The pseudocode of the steps carried out is provided in Algorithm 2. Upon receiving a request, EML enclave attests the application enclave (line 3) and assigns it an identifier made of the application identifier, the enclave identity, and the hash of the key established with that enclave during attestation (line 8). Next, EML enclave writes to storage tuple <eid, kα,EML, att, ⊥> to reflect the fact that enclave eid was attested and it is ready for provisioning. Finally, EML enclave acknowledges to C the end of the operation. If C does not receive an acknowledgement within a given timeout, then C may infer that the EML enclave handling the request has crashed and that the request should be issued to another EML enclave.

Termination/Suspension/Resumption Requests.

Algorithm 3 Termination Request

1: function TerminateRequest(eid)
2:     Parse eid as α||mrα||hα
3:     (key, st, col) ← GET(α; eid)
4:     if st == run then
5:         PUT(α; encα : (eid, key, tbd, col))
6:     end if
7:     SEND(ack, tbd, eid) to C
8: end function

Algorithm 4 Suspension Request

1: function SuspensionRequest(eid)
2:     Parse eid as α||mrα||hα
3:     (key, st, col) ← GET(α; eid)
4:     if st == run then
5:         PUT(α; encα : (eid, key, tbs, col))
6:     end if
7:     SEND(ack, tbs, eid) to C
8: end function

The pseudocode to terminate, suspend or resume an enclave is provided in Algorithms 3 and 4, respectively. Requests are invoked by C providing the enclave identifier eid as an argument. The EML enclave handling the request extracts the application identifier from eid and fetches from BSL attributes key, st, col of enclave eid. For enclave termination, the EML enclave checks that st is “run” and sets it to “tbd” (i.e., to be deleted). For enclave suspension, the EML enclave checks that st is “run” and sets it to “tbs” (i.e., to be suspended). For enclave resumption, the EML enclave checks that st is “sus” and sets it to tbd (i.e., to be run).

For termination and suspension of an enclave, EML only takes note of the request by setting the status variable of that specific enclave; the operation is actually completed at the beginning of the next lease. This is because, as we argued above, there is no guarantee that the cloud is effectively terminating or suspending the enclave at the time of the request. However, the enclave will stop working at the end of the current lease and its lease will not be renewed as shown below.

For enclave resumption, once again EML persists the request to storage by setting the status variable of that specific enclave; the enclave will be resumed by the main routine of EML that dispatches provisioning and resumption requests persisted to storage (see next).

Enclave Provisioning/Resuming. The pseudocode to dispatch requests to provision or resume enclaves is shown in Algorithm 4. This code is periodically executed by the EML enclave acting as master. Function FindNext(encα) on line 3 takes as input the list of tuples storing information about the enclaves of application α and returns the first tuple <eid, key, st, col> such that the status variable st is either “att” or “tbr”. Status “att” means that the enclave has been attested and it is ready to be provisioned with the application secret key. Status “tbr” reflects a suspended enclave that must be resumed. Before dispatching the request for eid, the EML enclave checks that the
number of running enclaves is below the upper bound set by application owner and that provisioning/resuming eid does not violate the owner’s constraints. Counting is carried out by function COUNTRUNNING(encα) on line 5. An enclave is considered as running if its status variable is set to “running, “to be suspended”, or “to be deleted”. Next, EML enclave either provisions eid with the application secret key and the current end-of-lease timestamp, or it sends to eid a “resume” directive with the current end-of-lease timestamp. Finally, EML writes to BSL that the enclave has been served and notifies C.

From this moment on, the application enclave runs as expected, e.g., executing computation on behalf of the application owner or serving requests from clients. However, we require the application to halt its execution if the current time has passed the current end-of-lease timestamp received by EML. Recall that a secure source of time is currently available on all SGX platforms via the sgx_get_trusted_time() API.

Lease Renewal. The pseudocode shown in Algorithm 7 is run by the EML enclave acting as master when the current end-of-lease timestamp is approaching. At this stage, the EML enclave scans through the list of enclaves belonging to application α and checks their status in order to determine whether the application must be suspended (line 4-5), deleted (lines 6-7), or whether its lease must be renewed. In the latter case, the application enclave receives the new end-of-lease timestamp col’ with a “renew” directive. Regardless of the operation, the EML enclave pushes the changes to BSL in order to persist the fact that the request was handled. Note that function DELETE(encα, eid) on line 7 removes from encα the tuple referring to eid and writes the updated list of tuples to storage.

C. Dealing with Application Shared State

Recall that some applications need to keep state to ensure its correct operation. Indeed, in a model where the cloud runs applications that span several enclaves, a shared storage layer might be required. This is because the sealing functionality of SGX is designed only to keep local state and does not allow state to be shared across enclaves. In this case, newly provisioned enclaves should maintain a consistent view of such a state—otherwise the security of the overall service might be at risk. For example, in S-NFV [32], the adversary could run two separated instances of the application and route state updates only to one instance, while exclusively pushing traffic flows to either instances. Hence, the outcome of processing a given flow may be different and dependant on whether it is carried out by one instance or the other. Similarly, password-strengthening services like Secretkeeper [23] rely on rate-limiting to keep passwords secret. Having access to multiple isolated application instances, allows the adversary to infringe the restriction imposed by the rate-limiting policy.

ReplicaTEE’s BSL can be used by such applications to share consistent state among their enclaves. Namely, whenever needed, authorized applications in ReplicaTEE can read/write their latest state from/to the storage layer using the offered PUT/GET interface. That is, our storage layer acts as consistent storage medium for various application enclaves to synchronize on their latest application state. For example, an enclave providing password-strengthening service can continuously write the number of trials attempted on the storage layer. This allows to enforce rate-limiting across all application enclaves running the same service. In Section V, we complement the evaluation of ReplicaTEE by assessing the overhead of using a BFT storage layer for applications that span across several enclaves.

D. Security Analysis

As mentioned in Section III-B, ReplicaTEE assumes an adversary that can compromise up to f storage nodes and all nodes that run the applications. However, the adversary
cannot compromise application enclaves since SGX ensures unhampered execution of code within enclaves as well as confidentiality of enclave data.

We note that even if the adversary compromises up to $f$ storage nodes, it cannot impact consensus realization in the storage layer. Namely, MinBFT [31] tolerates up to $f$ Byzantine nodes and ensures:

- Safety: all non-faulty storage nodes execute the requests in the same order (i.e., realize consensus).
- Liveness: all clients (i.e., EML enclaves) eventually receive replies to their requests.

In order to thwart forking attacks, one must ensure that (i) EML’s log of the enclaves belonging to an application, namely $enc_α$, reflects at all times the number and status of application enclaves deployed on $C$, and (ii) that the number of “running” enclaves in $enc_α$ is compliant with the policy defined by the application owner. Naturally, we must also cater for the confidentiality of the application secret key throughout the application life-cycle.

1) Secure Enclave Provisioning: We start by analyzing the security of the enclave provisioning process in ReplicaTEE. Recall that this process allows the owner of an application $α$ to securely provision his application enclaves by using the EML service. In line with current SGX deployment models, the only piece of information that we regard as sensitive is the application secret key $ak_α$, whereas the application binary is treated as non-sensitive data.

Before transferring the secret key of his application to EML, the application owner must attest the EML enclave and establish a secret key. This is done by leveraging the proxied attestation protocol of Section IV-A. Note that during key establishment, the EML enclave cannot attest the application owner (since the two parties may have not had any previous interaction). Therefore, EML accepts application metadata (i.e., the application secret key, the policy, etc.) from any party. Nevertheless we assume $C$ to authenticate application owners and that only authenticated application owners can contact EML. This is a reasonable assumption since $C$ must authenticate application owners in order to bill them.

Once the application owner has securely uploaded the secret application key $ak_α$ to EML, the security provisions of SGX guarantee the confidentiality of the key while it is stored in the memory of the EML enclave. If written to storage, $ak_α$ is encrypted and authenticated with keys that are only available to EML. Finally, EML securely delivers the key to the application after attesting the code of the enclave and after establishing a secure channel. Here again, attestation uses the proxied protocol of Section IV-A. However, attestation between EML and an application enclave allows the enclave to authenticate EML. This is achieved by embedding EML’s public key in the application code. By authenticating the prover, the application enclaves only accept provisioning from EML.

2) Ensuring Consistency of EML Operations: We now analyze how ReplicaTEE ensures that the number of running enclaves, for a given application, is always below the bound set by the application owner through the deployment policy. We achieve this by ensuring that all updates that affect the state of application enclaves are always registered by the storage layer that forms the backbone of ReplicaTEE. Given that the storage layer implements a consistent Byzantine fault tolerant storage service, all registered events are totally ordered on consistent storage. This design tolerates possible asynchrony or network partitioning that could arise in the EML layer. Namely, since EML enclaves do not run a consistent protocol (they only execute a lightweight node guarding protocol), consistency is guaranteed by the facts that (i) all operations handled by EML enclaves are duly registered on a consistent storage layer, and (ii) all operations executed by EML enclaves can be concurrently executed without the need for direct synchronization since the back-to-back execution of the same operation does not breach the security of ReplicaTEE. In what follows, we explain this in greater detail.

Provisioning/Resuming: Provisioning of an enclave $eid$ is only executed after the enclave has been attested and the request to be provisioned has been registered by writing the tuple $⟨eid, key, att, ⊥⟩$ to BSL (Algorithm 2, line 5). This tuple reflects the fact that $eid$ has been attested and it is ready for provisioning. Similarly, resuming of enclave $eid$ only occurs after the request has been registered by writing the tuple $⟨eid, key, tbr, col⟩$ to BSL (Algorithm 5, line 5). Notice that in both cases, the tuple written to storage carries the key established with the $eid$ at the time of attestation. This allows any EML enclave to establish a secure channel with that enclave in order to securely carry out requests.

Provisioning or resuming is carried out by Algorithm 6. Since BSL ensures that write/read operations are serialized, no other enclave will be provisioned or resumed before the request for $eid$ is dispatched. This holds despite the fact that the EML enclave in charge of handling the request for $eid$, say $e_{EML}$, may fail, and despite the fact that multiple EML enclaves may concurrently act as masters.

If $eid$ is to be provisioned and $e_{EML}$ fails right after provisioning the application enclave (Algorithm 6, line 5), the new master EML enclave will use the same secret key $key$ to establish a secure channel with $eid$ and provision the application secret key once again. Similarly, if $eid$ is to be resumed and $e_{EML}$ fails right after sending the “resume” command (Algorithm 6, line 9), the new master EML enclave will use the same secret key $key$ to establish a secure channel with $eid$ and send once again the “resume” command. In the above scenarios, we stress that provisioning or resuming the same enclave does not violate the security provisions of ReplicaTEE.

We point out that even if two (or more) EML enclaves acting as masters take in charge the request at the same time, they will both provision (or resume) $eid$. Also, they will both write the tuple $eid$, $key$, run, $col$ (Algorithm 6, line 10) to BSL in order to reflect that the operation has been dispatched. Once again, provisioning/resuming the same enclave and writing the same tuple to storage does not bring ReplicaTEE to an inconsistent state.
Only after the enclave status is set to “run” in BSL, EML enclaves will start provisioning/resuming another enclave. This ensures that provisioning/resuming of enclaves is carried out in strict sequential order and allows EML enclaves to be always aware of the running application enclaves for a given application.

**Terminating/Suspending:** As discussed before, once $C$ issues a request to terminate or suspend an enclave $eid$, there is no guarantee that the enclave has been effectively deleted or suspended. This is due to the fact that any attempt from EML to contact $eid$ may be dropped by the adversary that controls the communication network. For this reason, we resort to leases and require application enclaves to stop as soon as the current lease expires, unless EML renews it.

EML therefore treats an enclave $eid$ as suspended and sets its status accordingly (Algorithm 4, line 5) only at the end of the lease. At the time EML receives the request to suspend $eid$, it simply writes the request to BSL by setting $eid$’s state to “to be suspended” (Algorithm 4, line 6). However, the enclave is considered as running until the end of the current lease. A similar approach is taken for requests to delete an enclave $eid$. The request is written to BSL by setting $eid$’s state to “to be deleted” (Algorithm 4, line 7), however the enclave will be considered as running until the end of the current lease. At that time, the enclave metadata is deleted from storage (Algorithm 7, line 7).

Note that enclaves considered as running (i.e., the ones with status set to “running”, “to be suspended”, or “to be deleted”) affect the decision of whether a request to provision/resume an enclave should be completed. That is, an enclave is provisioned/resumed only if the number of enclaves considered as running is below the threshold set by the application owner (Algorithm 5).

**Lease Renewal:** At the end of a lease, EML proceeds to renew the lease to all application enclaves with status “running”. If an EML enclave crashes after renewing the lease to a given enclave $eid$, but before writing to BSL that the operation was completed (Algorithm 7, line 8), then $eid$ will receive the same renewal message from another EML enclave taking up the master role. Once again, repeating the lease renewal operation issuing the same end-of-lease timestamp to the same enclave does not constitute a security breach.

V. **Performance Analysis**

A. **Implementation Setup**

We deployed the storage service of ReplicaTEE on five identical servers with SGX supports. Each server is equipped with Intel Xeon E3-1240 V5 (8 vCores @3.50GHz) and 32 GiB RAM. The EML instances were deployed on a machine with Intel Core i5-6500 (4 Cores @3.20GHz) and 8 GiB RAM. All these machines are equipped with SGX to run enclaves and are connected with a 1Gbps switch in a private LAN network. We argue that this setting emulates a realistic cloud deployment scenario where the compute servers and their corresponding storage servers communicate over the cloud’s private LAN (e.g., Amazon AWS and S3).

| Application                        | Line of Codes (LoC) |
|------------------------------------|---------------------|
| MinBFT                             | 339                 |
| Proxied attestation (prover)        | 200                 |
| Proxied attestation & provisioning (verifier) | 800            |
| DupLESS integrated with ReplicaTEE | 80                  |

**TABLE I:** LoC required for implementing various routines of ReplicaTEE

As mentioned earlier, we instantiate the atomic storage service of ReplicaTEE using MinBFT. Our implementation of MinBFT uses 2 interface functions (createUI, verifyUI) and a total 339 LoC in SGX enclave in order to achieve Byzantine Fault Tolerance in the storage layer. We argue that this is small enough to make formal verification of the consensus layer code base as needed. In our evaluation, we relied on HMAC-SHA256 MACs to achieve authentication between replicas and clients. We stress that Byzantine failures do not affect performance of such classes of BFT algorithms.

We implemented the proxied attestation procedure described in Section IV-A based on the libraries provided by SGX SDK. To establish a secure channel during provisioning, we rely on SGX’s Diffie-Hellman key exchange library (256-bit ECC). In our proxied attestation implementation, the prover’s code in the enclave requires around 200 lines, while the verifier’s code in the EML enclave is around 800 lines (cf. Table I). In our implementation, we do not measure the latency incurred when communicating with the Intel Attestation service and we only measure the time of verifying the report issued by IAS.

B. **Evaluation Results**

In what follows, we evaluate the performance of ReplicaTEE in our setup. Namely, we measure the latency incurred in the provisioning of enclaves and in termination/suspension/resumption and lease renewal. Note that we do not evaluate the overhead incurred in the initial setup phase of EML and the initial code upload by ISVs, since the setup is carried out only once and the overhead for ISVs to upload their code to the cloud is not particular to ReplicaTEE and is incurred by all applications that leverage cloud-based SGX deployments.

We also measure the latency incurred in the provisioning of enclaves with respect to the achieved throughput. We measure the throughput as follows. The master EML enclave invokes operation in a closed loop, i.e., enclaves may have at most one pending operation. We require that the master EML enclave performs a series of back-to-back operations (requests) and measure the end-to-end time

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4We contrast this to Paxos (based on LibPaxos [31]) which requires around 4,000 LoC.

5The verifier enclave also includes JSON and Base64 decoder libraries [5], [8] in order to decode the response from IAS.
Enclave Provisioning: In Figures 3(a) and 3(b) we evaluate the throughput vs latency for the enclave provisioning process given different storage failure threshold \( f \). We see that when \( f = 1 \) (3 storage servers), the system achieves a peak throughput of 85 op/s with a latency of 270 ms. On the other hand, when \( f = 2 \) (5 storage servers), the latency remains almost the same, while the peak throughput is reduced to 75 op/s. Our findings suggest that the remote attestation process is the dominant factor in the operation latency. Notice that even if increasing the fault-tolerance threshold of BSL reduces the peak throughput (since it requires more communication rounds), it has limited impact on the witnessed latency.

Termination/Suspension/Resumption/Renewal Requests: Recall that termination, suspension, resumption, and renewal requests basically consist of the EML enclave updating the records corresponding to the target enclave on the storage layer. These requests are practically instantiated by a PUT request issued by the EML primary enclave to update the associated record. In ReplicaTEE, such PUT requests only consume 0.86 ms with a peak throughput of 9800 op/s when \( f = 1 \) and 0.94 ms with a peak throughput of 4700 op/s when \( f = 2 \).

DupLESS instantiation: In Figure 3(d), we evaluate the performance overhead incurred by ReplicaTEE on applications that require shared mutable state for their correct operation. To this end, we implement a variant of DupLESS and integrate it with ReplicaTEE in the case where \( f = 1 \). DupLESS is a server-aided encryption scheme that enables data deduplication over encrypted data. In this scheme, users interested in deduplicating their files first contact the DupLESS gateway to obtain an
encryption key that is derived to the file digest. This key is essentially a blind signature on the file digest that allows client to obtain encryption keys while keeping privacy of their files. By using a deterministic encryption scheme and a key derived from the file digest, two users with the same file will produce the same ciphertext that, as such, can be deduplicated by a storage service. By involving the gateway in the key generation process, brute-force attacks on predictable files can only be slowed down by rate-limiting the requests to the server. In our variant implementation, we integrate DupLESS’s blind signature scheme within SGX enclaves and use it as an exemplary application of ReplicaTEE. Namely, we rely on ReplicaTEE to automatically commission and decommission DupLESS enclaves and to allow running enclaves to synchronize on their latest state to effectively enforce rate-limiting across all running enclaves. Since DupLESS leverages RSA-based blind signatures, we utilize the SGX-SSL library to implement the signing functionality (with 4096-bit RSA) with 80 lines of code. We deploy the DupLESS servers on a machine with Intel Xeon E3-1240 V5 and evaluate the overhead introduced by ReplicaTEE in this setting when compared to a standalone DupLESS gateway that does not leverage any functionality from SGX (i.e., the standard DupLESS gateway described in [11]).

Our results show that the latency incurred by a standalone DupLESS gateway is 18 ms with a peak throughput of 330 op/s. On the other hand, integrating a single DupLESS instance in ReplicaTEE achieves almost the same performance. This confirms that ReplicaTEE does not add significant overhead to existing SGX-based enclaves. Notice that adding an additional DupLESS enclave almost doubles the peak throughput by reaching around 600 op/s (for 2 DupLESS instances). The throughput exhibited by a distributed DupLESS instantiation will be however limited by the peak throughput exhibited by BSL, which is roughly 9800 op/s; in this case, BSL can accommodate for roughly 30 DupLESS instances. We stress that replicating DupLESS using ReplicaTEE does not have any noticeable impact on the latency witnessed by DupLESS users.

VI. RELATED WORK

To the best of our knowledge, no previous study has addressed the problem of enabling seamless replication of SGX enclaves in the cloud. We now briefly review related work in the area.

Gu et al. [22] provide an SDK to enable enclave migration in the cloud. Here, enclaves are augmented with a thread that carries out state transfer. The thread in the source enclave brings other threads to a quiescent state and ships the internal state to the target enclave; a thread in the target enclave receives the state, installs it and recover execution. Since some state information is only available to the platform, the authors use a number of heuristics to estimate that part of the state and transfer it to the target platform. The authors show that their heuristic are indeed effective in few application scenarios. However, the effectiveness of this heuristic for general SGX applications remains to be assessed.

Matetic et al. [29] proposed a scheme, ROTE, to enable rollback protection for SGX enclaves. Recall that the sealing functionality of SGX provides confidentiality and integrity but does not guarantee freshness of sealed data. In a rollback attack, a malicious host leverages this shortcoming to provide enclaves with stale state information. In ROTE, a set of ROTE Enclaves running on different platforms, help one application enclave to maintain monotonic counters that, when used in conjunction with the sealing functionality of SGX, provide state freshness. The set of ROTE enclaves is static and must be setup by an administrator before applications can leverage the service. Notice that ROTE does not deal with applications that span across several enclaves and requires that the application enclave runs on one of the platform that hosts ROTE enclaves.

ICE [33] is another proposal that addresses rollback attacks in SGX. Differently from ROTE, ICE is a “stand-alone” solution that relies on hardware modifications to the platform, including dedicated on-chip registers backed by off-chip NVRAM.

Brandenburger et al. [12] address forking attacks on TEEs in application scenarios where multiple clients interact with an enclave running at a malicious host. In order to counter forking attacks, they require an enclave to create a hash chain with the history of all performed operations. When combined with monotonic counters shared with all clients, such an approach can ensure fork linearizability [29].

Proxyed attestation was first proposed in [24]. Here, the proxy is registered with IAS and acts on behalf of the (unregistered) verifier towards the IAS. Notice that [24] leverages a proactive attestation scheme where the enclave itself requests a quote from the platform and binds it to its ephemeral DH key before seeing the ephemeral DH key of the verifier. This design saves round-trips during attestations but is not compliant with the SDK of Intel SGX; namely, a quote is provided after the ephemeral DH key of the verifier has been received and a shared key established. Therefore, the scheme of [24] requires application developer to update their code in order to account for changes in the attestation protocol. Furthermore, the attestation protocol proposed in [24] only provides an unilaterally authenticated DH key exchange, since the enclave cannot be sure that the ephemeral DH key is the one chosen by the verifier and not by the proxy. Mutually authenticated DH key exchange would require the enclave to embed the verification key of the verifier. However, this is not viable if the enclave is meant to be verified by any (previously unseen) user of the cloud service.

[Note: The data structure providing the quote is referred to as msg3 in the SDK [3] which is returned by sgx_ra_proc_msg2() that processes the ephemeral DH key of the verifier and a valid signature on that ephemeral key.]

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6 We chose DupLESS because it incurs minimum I/O and allows us to clearly evaluate the computational overhead of ReplicaTEE.
VII. Conclusion

In this paper, we presented a novel solution, ReplicaTEE, that enables dynamic replication and decommissioning of TEE-based applications in the cloud. ReplicaTEE leverages an SGX-based provisioning service that interfaces with Byzantine Fault Tolerant storage layer to orchestrate dynamic application replication in the cloud without the active intervention of the application owner.

We showed that ReplicaTEE withstands a powerful adversary that can compromise a large fraction of the cloud infrastructure. By means of a prototype implementation, we also showed that ReplicaTEE moderately increments the TCB and does not add significant overhead to existing SGX-based applications.

ReplicaTEE therefore emerges as the first secure and practical solution to support elasticity of TEE-based applications in the cloud. As such, ReplicaTEE enables applications from benefitting from high availability, performance, and cost effectiveness that essentially form the basis of the cloud-computing paradigm.

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APPENDIX

MinBFT comprises four routines and unfolds as follows:

1) **Request**: Clients send their request messages asking the replicas to execute certain operations. A client \( C \) prepares its requested operation \( op \) in message \( (\text{REQUEST}, C, \text{seq}, \text{op})_{\sigma_C} \), where \( \text{seq} \) records the (local) message sequence from each client to prevent re-execution of the operations, and \( \sigma_C \) is the client signature.

2) **Prepare**: This phase is triggered when the primary \( S_p \) receives a request message \( m \). Once the request is validated, the primary asks its TEE to generate a unique message identifier \( UI_p = \langle c, m \rangle_{\sigma_p} \). Note that the counter \( c \) is monotonically increasing and the signature \( \sigma_p \) is from the TEE. Subsequently, \( S_p \) multicasts \( (\text{PREPARE}, v, S_p, m, UI_p) \) to the other replicas.

3) **Commit**: This phase serves to acknowledge a valid \text{PREPARE} message. Each replica \( S_i \) responds with a \text{COMMIT} message. In particular, each replica multicasts \( (\text{COMMIT}, v, m, S_i, UI_i, S_p, UI_p) \), where \( UI_i \) is a unique identifier that \( S_i \) gets from its TEE.

4) **Reply**: A request is committed locally and can be executed once a replica has received enough (i.e., \( f + 1 \)) consistent commits, because it is ensured that any request that commits locally on a correct replica will be committed on at least \( f + 1 \) correct replicas eventually. Therefore, the replica can execute the operation \( op \) and send the reply \( (\text{REPLY}, S_p, \text{seq}, \text{res}) \) with the execution result \( \text{res} \) back to the client.

5) **View-Change**: When a primary is suspected to be misbehaving, a replica can request a replacement of the primary through the view-change procedure. For example, when a received request failed to be executed within a certain timeout, a replica multicasts a view-change request \( (\text{REQ} \rightarrow \text{VIEW} \rightarrow \text{CHANGE}, S_i, v, v') \), where \( v' \) is the new view number and \( v' = v + 1 \). If a replica receives \( f + 1 \) \text{REQ} \rightarrow \text{VIEW} \rightarrow \text{CHANGE}, it moves to view \( v' \). At this stage the replica multicasts \( (\text{VIEW} \rightarrow \text{CHANGE}, S_i, v', CP, O, UI_i) \), where \( CP \) is the latest certificate and \( O \) is the set of all messages sent by the replica since \( CP \). Once the new primary of view \( v' \) receives \( f + 1 \) valid \text{VIEW} \rightarrow \text{CHANGE} messages with consistent system state, the view change is executed by the new primary who broadcasts message \( (\text{NEW} \rightarrow \text{VIEW}, S_{p'}, v', V_{vc}, s, UI_{p'}) \), where \( V_{vc} \) is the view-change certificate that includes all the received VIEW \rightarrow CHANGE messages, and \( s \) is the current system state which will serve as the initial state of view \( v' \).

The correctness of MinBFT holds as long as there is at least one honest node involved in any two quorums, thus only \( 2f + 1 \) replicas are required to tolerate \( f \) faulty nodes. Further details on MinBFT can be found in [34].

DupLESS [11] allows clients to derive encryption keys for secure deduplication in cloud-based storage. Key derivation is performed in DupLESS by means of an interactive protocol between a client and a gateway based on RSA blind-signatures. The protocol is sketched in Figure 4.

The client computes the hash of the file \( M \) and blinds it with a random value \( r \) that he raises to the public exponent \( e \). He transmits the blinded hash value to the gateway. The gateway now signs the blinded value with its private exponent \( d \). The gateway finally transmits the signed blinded hash back to the client. As \( cd \equiv 1 \mod \phi(N) \), we have that \( y \equiv (hr)^d \equiv h^d r^d \equiv h^d \mod N \). The client can compute the \( r^{-1} \mod N \), remove the blinding from \( y \) and obtain the signed hash \( h^d \mod N \). The client needs to check the validity of the signature using the public exponent of the gateway \( e \). If the signature is valid, the generated symmetric key will be the hash of the signed hash of the file \( K = H(z) = H(h^d) \).

The benefits of such a key generation protocol are two-fold:

- Since the protocol is oblivious, it ensures that the gateway does not learn any information about the file.
- On the other hand, this protocol enables the client to check the correctness of the computation performed by the gateway (i.e., verify the gateway’s signature). By involving the gateway in the key generation process, brute-force attacks on predictable messages (i.e., files) can be slowed down by rate-limiting key-generation requests to the gateway.

| Client | Gateway |
|--------|---------|
| \( h \leftarrow H(M) \) | \( r \leftarrow Z_N \) |
| \( x \leftarrow h \cdot r^e \mod N \) | \( y \leftarrow h \cdot r^e \mod N \) |
| \( z \leftarrow y \cdot r^{-1} \mod N \) | \( y \leftarrow x^d \mod N \) |

If \( z \equiv h \mod N \) then ret \( \perp \)

Else ret \( K \leftarrow H(z) \)

Fig. 4: RSA blind-signature scheme adapted from [11]. \( H : \{0, 1\}^* \rightarrow Z_N \) denotes a hash function, \( N \) the RSA modulus, \( e \) the RSA public exponent and \( d \) the RSA private exponent.