Sealed Computation:
Abstract Requirements for Mechanisms to Support Trustworthy Cloud Computing

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Abstract. In cloud computing, data processing is delegated to a remote party for efficiency and flexibility reasons. A practical user requirement usually is that the confidentiality and integrity of data processing needs to be protected. In the common scenarios of cloud computing today, this can only be achieved by assuming that the remote party does not in any form act maliciously. In this paper, we propose an approach that avoids having to trust a single entity. Our approach is based on two concepts: (1) the technical abstraction of \textit{sealed computation}, i.e., a technical mechanism to confine the processing of data within a tamper-proof hardware container, and (2) the additional role of an auditing party that itself cannot add functionality to the system but is able to check whether the system (including the mechanism for sealed computation) works as expected. We discuss the abstract technical and procedural requirements of these concepts and explain how they can be applied in practice.

Keywords: security requirements, trusted computing, trustworthy computing, cloud computing, cloud service, auditor

1 Introduction

Cloud computing has become widespread as it allows for supplying and utilizing computation resources in an on-demand fashion. This reduces cost, increases flexibility and improves infrastructure scalability [19]. Cloud computing is increasingly being adapted for services provided by networks of small devices, commonly referred to as the Internet of Things (IoT). IoT Cloud [2] or “Cloud of Things” (CoT) [1] provides resources such as storage, analytics tools and shared configurable computing resources to reduce the cost and complexity associated with the IoT systems.

When the data processing and storage are delegated to a cloud provider, users of cloud services usually have to trust the cloud provider to act as expected. However, in common cloud deployments, there is no technical guarantee that a single malicious insider like a system administrator or a person with physical
access to the cloud infrastructure does not tamper with code and data. Hence cloud clients should be provided some technical guarantees and indications that the cloud service is trustworthy.

As an example, consider the scenario of an IoT Cloud implementation for usage-based insurance (UBI) [16], a novel car insurance business model, where the insurance company calculates premiums based on drivers behavior using actual driving data.

In UBI, participating cars are equipped with a telematics devices to collect driving data such as location, speed, acceleration, cornering, and other details. Driving data are processed to get a ranking based on personal driving behavior. Using the driver ranking, the insurance company calculates a customized premium to the policyholder employing a more accurate risk estimate, reducing incurred losses [9] [25] and offering a bonus in the case of good driving behavior.

UBI promises many benefits such as, for the insurance companies, reducing incurred losses through accurate risk estimates [25] [9] and, for the policyholders (drivers), improving their driving style through feedback and decreasing their premiums. But obviously, UBI also raises concerns, such as user discrimination [16], and consumer privacy [25] [9].

Figure 1 depicts an abstract view of UBI: The service provider may actually be the same entity as the insurance company, but in many business implementations (BonusDrive by Allianz [4], SmartDriver by HUK-Coburg [15]) it is a different company. One reason for separation is that insurance companies do not have the corresponding know-how to compute the driving ranking. Another reason is that the insurance companies want to mitigate consumers privacy concerns by stating that they have no access to the behavioral data, as it is processed by a third party [5].
Users who process sensitive data in the cloud have the following general security requirements:

- Confidentiality of data: Policyholders agree that their ranking is computed, but they want their individual usage data to remain confidential towards the insurance company and the cloud provider.
- Confidentiality of code: Service providers want to protect their intellectual property from other parties, in particular the insurance company and the cloud provider. So the software which is deployed in the cloud should be protected.
- Integrity of data and code: Insurance company, service provider and the policyholders should have a guarantee that the cloud provider does not change data or code in any unauthorized way.

On the one hand, users establish a sense of trust in the cloud provider in practice via contracts over Service Level Agreements (SLAs), auditing certificates and reputation.

Unfortunately, even with the most refined SLAs the necessity to place trust in the cloud provider remains.

On the other hand, numerous technical approaches [18] have been proposed to achieve security requirements such as those above using trusted hardware. For example, hardware security modules (HSMs) [10] [26], i.e., tamper-resistant physical computing devices, can perform secure and confidential computation of data. Using HSMs, it is possible to deploy specific software modules, create cryptographic keys and process data purely within the hardware device. Returning to our UBI scenario, the HSM can be used to effectively protect the service provider’s data and code from the cloud provider. However, in this case the necessity to trust a single entity is not avoided, it is merely shifted from the cloud provider to the trusted hardware provider. This observation is not specific to HSMs but holds also for other such technologies such as Intel SGX [6] [24].

1.1 Contributions

In this paper, we propose a general approach that ensures generic confidentiality and integrity of cloud service and that avoids the necessity of having to trust a single entity.

Our approach is based on the combination of two concepts:

1. *Sealed computation*, an abstract technical mechanism to confine the processing of data within a tamper-proof hardware container (like a HSM), and
2. a procedural mechanism of mutual checking applying the additional role of an *auditing party*, which is necessary to check whether the system works as expected, but cannot modify it.

We describe the abstract technical and procedural requirements of both concepts and argue that they are sufficient to achieve the generic security properties described above. In the spirit of work by Morris Jr. [20], our work is conceptional,
avoiding over-formalization but still providing clear definitions and evaluating statements. The main insight is to show how an abstract hardware mechanism (sealed computation, solely defined by its requirements) must be utilized in the cloud service such that the necessity to trust in a single entity is avoided.

Similar to other work [24, 6], this paper focuses on integrity and confidentiality properties and do not consider availability. We use the UBI scenario above repeatedly as an example to illustrate our exposition, it generalizes to many other scenarios.

1.2 Outlook

We first define the concept of sealed computation in Section 2. Then the system and attacker model is presented in Section 3. Section 4 describes the procedural mechanism applying the role of an auditor.

In Section 5 we provide a security analysis and argue that general security requirements are satisfied unless two parties act maliciously. Related work is discussed in Section 6. Finally, Section 7 concludes the paper.

2 Sealed Computation

While data at rest can, typically, be protected by encryption, while protecting data during processing commonly is still an interesting problem to solve. We introduce a definition of sealed computation using abstract roles to keep it general, later, these are mapped to the parties introduced in Section 3. The term *sealed computation* is an abstraction that describes a well-defined level of protection against such attackers. Intuitively, this is done by encapsulating the software execution within a physical piece of hardware. We utilize the notion of sealed computation to maintain the integrity and confidentiality requirements of the system.

2.1 Definition

In sealed computation, a party $A$ provides a physical execution container $C$ into which a party $B$ may “seal” its software. The container $C$ ensures that the software is running in an unmodified fashion. Furthermore, $C$ also guarantees that only a restricted set of interactions with the software are possible through a well-defined interface. Apart from that, no information is leaked from within $C$ to the outside, not even to $A$ the provider of the container nor the software provider $B$.

More formally, let a party $A$ provide a physical execution container $C$ and party $B$ provide a software $M$ which implements some input/output specification via a well-defined interface. The interface can be thought of as a description of input/output signals over wires or the format of incoming or outgoing protocol messages.
Definition 1 (Sealed Computation). We say that $B$ seals $M$ within $C$ provided by $A$ if the following technical requirements are met:

- (Sealing) $A$ and $B$ cannot access the code and data of $M$ after it has been sealed within $C$, apart from changes allowed by the interface.
- (Attestation) As long as $M$ has not terminated and as long as $A$ acts honestly, $C$ can provide evidence which proves that $C$ is running software provided by $B$ in a manner which is unique to the sealing instance, i.e., any change of $M$, $C$ or any subsequent sealing using the same combination will result in different evidence.
- (Black-box) Information flow between $M$ and any other party (including $A$ and $B$) is restricted by the interface specification of $M$, i.e., nothing about the internal state of $M$ (code and data) can be learned apart from what is given away via the interface.
- (Tamper-resistance) Any usage of $M$ that does not satisfy the interface specification results in termination of $M$ and the destruction of $C$ such that neither code nor data from within $C$ can be retrieved.

Intuitively, the Sealing requirement of sealed computation binds the execution of a program to a particular hardware environment. The requirements of Black-box and Tamper-resistance limit access to data and code only to interactions given in the functional specification of $M$: Black-box restricts information flow for expected interactions, while Tamper-resistance does this for unexpected interactions.

The Attestation requirement enables external parties to validate the fact that $M$ has been sealed. It implies that $C$ contains some known unique characteristic that can be validated by checking the provided evidence. This validation, however, depends on the correctness of $A$. A common realization of this is for $A$ to embed a secret key within $C$ and allow external parties to validate its existence by providing the corresponding public key. The existence of such a unique characteristic implies that it is possible to establish an authentic and confidential communication channel to $M$ once sealing has started.

Similarly, note that $B$ or any user of $M$ still has to rely on $A$ to act honestly because it is not verifiable whether $C$ actually implements sealed computation. However, if $B$ correctly seals $M$ within $C$ provided by an honest $A$, even $A$ cannot change $M$ afterwards and the tamper-resistance requirement of $C$ protects all secrets within $M$ that are not accessible via its interface or before sealing.

2.2 Confidential Software Deployment

The notion of sealed computation is a powerful abstraction that can be used to describe techniques that protect software also during deployment. We now argue that the technical requirements of sealed computation allow to ensure the confidentiality of the code which is sealed.

Intuitively, the idea of confidential software deployment is for $B$ to initially install within the sealed computation a loader stub which is able to load the
final user program specified by $B$ into $C$. Within the sealed computation, this 
software is decrypted, installed and then takes over the final interface operations 
expected by the users. This loader stub can be part of the sealed computation 
mechanism from the start. Since it can be easily added to any mechanism that 
satisfies Definition 1, we did not include it as an additional requirement in that 
definition.

Observe that $M$ cannot be assumed to remain confidential if $A$ is untrust-
worthy. However, if $A$ is trustworthy, sealed computation can be used to run 
code that remains confidential even towards $A$.

3 System and Attacker Model

3.1 Participants

For a general cloud-based application system model, our approach assumes the 
following main participants - referred to as entities or parties interchangeably:

1. **Data Prosumer (DP):** The DP is a producer and/or consumer of data at the 
same time, i.e., it produces input data and/or has an interest to consume 
the computed results. The way in which data is processed by the application 
is described by the DP in the form of a **functional specification**.

2. **Application Software Provider (ASP):** The ASP develops and maintains the 
analytics software which processes the data in the cloud and computes de-
sired results according to the functional specification.

3. **Cloud Provider (CP):** The CP provides the cloud service which includes 
the hardware infrastructure, the software, and all associated configuration, 
administration and deployment tasks. The CP is also responsible for the 
security of the system as well as its availability towards the DP.

4. **Auditing Party (AP):** The AP is an independent party that helps to en-
sure the integrity of the hardware and software before the system becomes 
operational. We simply refer to the AP as the **auditor**.

5. **Sealed Computation Provider (SCP):** Additional entity to be considered is 
the SCP provides the sealed computation technology.

To map the sealed computation definition in Section 2 to the UBI scenario, it 
may help to think of the execution container $C$ being a specific HSM provided 
by party $A$ (the SCP), while party $B$ is the service provider (SP) who wrote 
software $M$ on behalf of insurance company (DP).

3.2 User Security Requirements

The desired security requirements of the parties are described in more detail here. 
Every requirement has a name that is prefixed by the corresponding participant 
role.

**Definition 2 (User Security Requirements).** The participants have the fol-
lowing security requirements:
– (DP-Privacy) The DP requires that data remains confidential to any other party, i.e., neither CP, nor ASP, nor AP, nor SCP can learn anything about the data.

– (DP-Integrity) Results which are obtained from the system by the DP are correctly computed on data as provided according to the functional specification. DP-Integrity covers data storage and processing integrity.

– (ASP-Integrity) The analytics software provided by the ASP is executed in an unmodified form within the system. Note that ASP-Integrity does not imply DP-Integrity since the latter refers also to data.

– (ASP-Confidentiality) No other party except the AP is able to learn about the analytics software developed by the ASP apart from what is described in the functional specification.

3.3 Attacker Model

In this section, we formulate the attacker model. First, the ways in which individual participants may maliciously misbehave are described (the local attacker assumption). Then we define a condition that restricts the number of parties that may act maliciously (the global attacker assumption). The participants may act as follows:

– Application Software Provider (ASP): The ASP could provide an analytics software that leaks information about the processed data, thus violating DP-Privacy. Also, the ASP could violate DP-Integrity by providing software that incorrectly computes the results, i.e., computes the results not according to the functional specification provided by the DP.

– Sealed Computation Provider (SCP): The SCP could provide an incorrect sealed computation mechanism, i.e., a mechanism that has back-doors or vulnerabilities that enable changing code and data, thus violating ASP-Integrity or DP-Integrity, or a system that leaks code or data which violates ASP-Confidentiality or DP-Privacy.

– Cloud Provider (CP): The CP could leak any software that it has access to a malicious party, thereby violating ASP-Confidentiality. The CP has physical access to the mechanism provided by the SCP so it may attempt to access and/or modify data that is stored/processed, thus violating ASP-Integrity, DP-Integrity or DP-Privacy.

We assume, however, that the CP protects its systems from interference and misuse by external attackers that are not specific to our scenario. Therefore these attacks are excluded from consideration in this work.

– Auditing Party (AP): During checking, the AP could try to add functionality to the system to leak information about the processed data and/or the software, thereby violating DP-Privacy or ASP-Confidentiality directly.

3 While privacy has many definitions, here we explicitly use the term Privacy and not Confidentiality to emphasize end users’ privacy (as individuals) against the providers and operators of the system (as organizations).
If any party acts in ways described above we say that this party acts maliciously. A party that does not act maliciously is considered honest.

For reasons of simplicity, the DP is excluded from our attacker model. Typical misbehavior of the DP can be giving a wrong functional specification, providing false data or to reveal the received results to any other party. Correct behavior in this respect cannot be enforced using a trustworthy cloud service as we envision here. Therefore, the DP is assumed to always be honest.

The global attacker assumption, i.e., a restriction on the number of parties that may act maliciously is formulated as follows: either the AP or both SCP and ASP are honest. More precisely, if the identifiers are taken as Boolean predicates of whether they are acting honestly or not, then the global attacker assumption is satisfied if the following condition holds:

\[ AP \lor (SCP \land ASP) \]

Note that the condition is independent of the actions of the CP, and that it does not state which party exactly acts maliciously (AP, SCP or ASP).

### 3.4 Availability of Remote Attestation

To establish trust, it is often necessary to use mechanisms for remote attestation. Following the terminology of Cocker et al. [8], attestation is the activity of making a claim to an appraiser about the properties of a target by supplying evidence which supports that claim. An attester is a party performing this activity. The result of an attestation depends on a mixture of facts that the appraiser can check directly on the evidence provided by the attester (e.g., cryptographic signatures) and trust in the attester itself (the mechanism by which the evidence was generated). Any party being part of a remote attestation has the requirement that the directly checkable part of the attestation works as expected. In practice, this means that the used cryptography (e.g., digital signatures) is secure and that honest parties protect their cryptographic secrets.

### 4 Combining Sealed Computation with an Auditor

One application of sealed computation in cloud computing would be for the CP to offer a mechanism to its “customers” DP and ASP to perform a sealed computation on the provided cloud hardware. In this case SCP and CP would be the same party. However, note that utilizing sealed computation alone is not sufficient to ensure the participants’ security requirements because (1) sealed computation does not guarantee anything before sealing takes place, and (2) the mechanism of sealed computation cannot be trusted without means to verify its function. We will therefore treat CP and SCP as independent parties.

#### 4.1 The Role of Auditor

The sealed computation is combined with the role of an auditing party AP to establish the security requirements described in Definition 2. In general, auditors
are known to usually perform independent checks and assess other entities in terms of service, performance, security and data privacy and system operations [14]. We use the AP to both guarantee the functionality of the sealing mechanism provided by the SCP and to verify the functionality of the analytic software provided by the ASP. Once sealing has taken place, the mechanism of sealed computation ensures continued trust in the system without having to interact with the AP anymore.

The auditor is not allowed to add or modify functionality in the system. This is ensured by a mutual checking procedure described below. The AP, however, has to enable a possibility of attestation which is independent of the SCP. This can be realized by either providing an independent mechanism or (better) by adequately configuring an attestation technique that is already presented in the sealed computation technology (e.g., by embedding a secret within the physical container of sealed computing).

Figure 2 illustrates the structural model with the roles and responsibilities of each participant. The idea is to base the well-functioning of the system on the assumption that either the auditor or all parties checked by the auditor are honest during critical phases of system operation. While commonly the DP had to trust the CP exclusively, it now must rely on trust either in the SCP and ASP or the AP (a condition expressed in our global attacker assumption above).

To illustrate the different roles using our introductory UBI scenario, the policyholders and the insurance company share the role of the DP. The insurance company defines the functional specification of the driver ranking based on which the ASP develops the analytic software. The SCP could be a provider of the sealed computation container (like a HSM) and the AP would be a company like a certified public accountant, that is able to perform code and security audits.
on hard- and software. The SCP is assumed to have appropriate security mechanisms in place against attacks by parties not considered above (e.g., hackers and cybercriminals). Regarding remote attestation, the HSM provides certificates with which attestation evidence generated by the HSM can be verified [27].

4.2 Trust Establishment Procedure

For simplicity and comprehension of discussion we distinguish the execution lifetime of the system model into mutually exclusive phases: the Checking phase and Running phase. During the Checking phase, the trust establishment procedure takes place, while the Running phase begins with the service start-up. During the Running phase, the DP can upload data and get results and the CP operates the cloud system.

The exact actions and obligations of the participants and interplay among each other are described as trust establishment procedure below. This procedure can be regarded as a form of procedural requirement which in combination with the technical requirements of Sealed Computation allows to fulfill the user requirements.

Definition 3 (Trust Establishment Procedure with Mutual Checking).

The participants undergo the following procedure:

1. Trust establishment in analytics software:
   (a) The ASP prepares the analytics software ready to be deployed.
   (b) The AP verifies whether the analytics software satisfies the functional specification and does not leak any information about the processed data.
   (c) At the same time, the ASP ensures that the AP does not change any functionality of the analytics software.
   (d) As a result of this procedure, ASP and AP generate public evidence to be produced by an attestation mechanism by which it can be verified that the checked version of the software is running in the sealed computation (e.g., a hash of the binary code that can be attested).

2. Trust establishment in sealed computation mechanism:
   (a) Before the sealed computation system is shipped and deployed, regardless of the deployment model, the SCP prepares the sealed computation mechanism (hardware and software, including the possibility for confidential software deployment).
   (b) The AP verifies (off-line) the integrity of the sealed computation mechanism, i.e., the entire hardware and software system. This includes a physical check for the security measures, policy compliance, data security and data privacy, functional check also of the confidential software deployment mechanism.
   (c) At the same time, the SCP ensures that the AP is not adding new functionality during these checks, i.e., that the AP is behaving according to the auditing procedure specifications.
(d) The AP and the SCP generate public evidence that enables attestation of
the sealed computation mechanism, e.g., by embedding independent pri-
vate keys within the sealed computation container to which they possess
the corresponding public keys.

3. The sealing mechanism is started in the presence of AP and SCP. At this
time the auditing procedure ends and both SCP and AP can leave the deploy-
ment site which is run by the CP.

4. Using the confidential deployment procedure, the ASP loads the code that was
checked by the AP in Step 2 above.

5. The AP and the SCP must be present any time when the system and/or the
sealed computation mechanism is reset/restarted, is under maintenance or
shall be changed. In such cases the AP and the SCP must re-check the system
and both must re-enable the attestation mechanism as described in the above
procedure.

The result of this procedure are two pieces of public evidence that all parties
can use to verify their security requirements:

– Public evidence provided by AP and SCP that DP, CP and ASP can use to
verify that an instance of sealed computation is running.

– Public evidence provided by AP and ASP that can be used to verify that a
particular software is running within the sealed computation.

5 Security Analysis and Discussion

5.1 Security Analysis

To argue that the security requirements from Def. 2 are met, we make the fol-
lowing introductory observation: The sealed computation mechanism defined in
Def. 1 will not be in the Running phase if the ASP software or the sealed com-
putation mechanism is not correct.

To see this, we make a case distinction based on the global attacker assump-
tion which states that all parties can act maliciously as long as the global attacker
assumption is satisfied, i.e., either the AP or both the ASP and the SCP behave
honestly. There are three possible cases for parties to act maliciously during
the checking phase when the trust establishment procedure (Definition 3) takes
place:

– The ASP is malicious: If the ASP is malicious, then the AP must be honest.
So if the ASP acts maliciously and implements an incorrect software then
the checking procedure (Step 1.b) mandates that the AP checks the soft-
ware correctness. Since the AP is honest, it will detect the incorrectness of
software, the check will fail and the Running phase will not take place.

– The SCP is malicious: If the SCP is malicious, then the AP must be honest.
So if the SCP is not honest, the sealing container may not be implemented
correctly. However, the checking procedure (Step 2.b) requires the AP to
check whether the sealed computation requirements are met. Since the AP is honest, it will detect incorrectness and the Running phase will not be entered.

– The AP is malicious: If the AP is malicious, then the ASP and the SCP are both honest. In this case, the analytics software and the sealed computation mechanism are correct from the beginning. Furthermore, the mutual checking procedure (Steps 1.c and 2.c) requires that both ASP and SCP ensure that the AP does not manipulate the functionality of the analytics software or the sealed computation mechanism. So if the Running phase is entered, the sealed computation mechanism and the analytics software are both correct.

Therefore, under the attacker assumption, the establishment procedure guarantees that the system will not enter the Running phase unless it is working properly as defined in the specification.

Subsequently, during the Running phase, the sealed computation mechanism (Definition 1) takes over to guarantee the desired requirements. To argue for the fulfillment of ASP-Integrity and DP-Integrity, the Sealing and Tamper-resistance requirements of the sealed computation ensure that content (data and code) in the sealed container cannot be improperly modified. Furthermore, the Black-box requirement restricts information flow such that DP-Privacy and (assuming confidential deployment) ASP-Confidentiality are maintained.

5.2 Discussion

While our results are conceptual, they provide a preliminary guideline of building a trustworthy cloud computing service in which cloud customers can trust that cloud providers and operators cannot access their data and code. In essence, sealed computation may not be a brand new concept, as sealed storage was defined by Morris [20]. Whereas, to the best of our knowledge, sealed computation was not formally defined comprehensively before. Any computational implementation that satisfies the requirements defined in Definition 1 can be considered a sealed computation mechanism. However, in practice, one may argue that any assumption like the security of cryptography or requirements like Black-box of any hardware device only hold with a certain probability, so the guarantees in practice never hold with 100%. One may also argue that many parts of the procedures described in Definition 3 are also rather hypothetical and cannot be realized fully in practice. For example, the AP is assumed to perfectly verify the correctness of the software of the ASP (in Step 1b) against the functional specification. While software verification has come a long way, it still is restricted by the size and complexity of the software system. Another example that appears far from practice is the statement that the AP can verify the correctness of the sealed computation container (hardware and software) provided by the SCP (in Step 2b). It is well-known that the production of hardware is a very complex process involving lots of different technologies. The resulting chips are rather non-transparent and need complex validation equipment to be checked.

Useful insights can be inferred from the proposed approach. While the AP is one party in our model, in practice it can consist of multiple independent
auditing actors, e.g., different companies that all check independent parts of the system and mutually certify the results towards each other. The collection of auditors in its entirety then forms the AP, meaning also that all “sub-auditors” must behave correctly for the AP to be regarded as honest. In practice, these sub-auditors are even often part of the same company, albeit in different parts that are independent of each others (like software development and testing departments).

Another highlight is, it is possible to delegate security enforcement to trusted hardware without having to trust a single entity. However, during the Checking phase, the AP must be continuously present until the sealed computation container runs, and it must be possible to establish attestation evidence which is independently supported by the AP and the SCP (for the sealed computation container) and by the AP and the ASP (for the analytics software). These points result from the requirement of mutual checking, i.e., not only does the AP verify the actions of ASP/SCP, but also ASP/SCP need to prevent the AP from slipping in new functionality to software and hardware, a detail which is often overlooked or (unconvincingly) excluded by the assumption that the AP is always honest. Being able to embed shared attestation credentials of mutually untrusted parties in a single trusted hardware container is a feature which is — at least to our knowledge — not supported by any currently available trusted computing mechanism [18].

So overall, the proposed approach presents an idealized version of system construction and deployment processes which can serve as an orientation for practice towards achieving a trustworthy service.

6 Related Work

Privacy is a major factor in trusting data and computation outsourcing, such as in a cloud-based application. Hence trust establishment has been discussed in the context of cloud from different perspectives in the literature, we distinguish them into technical and non-technical trust enhancement approaches. Georgiopoulou and Lambrinoudakis [13] reviewed a number of trust models for cloud computing trying to provide a gap analysis in the literature. However, the review considered only a very limited set of models.

Non-technical approaches have been developed and used ranging from SLAs and recommendations for security architecture, risk management and operational teams. For example, Alhanahnah et al. [3] studied a trust evaluation framework to allow cloud customers to choose among set of cloud providers based on trust levels. The authors distinguished trust factors into two sets: SLA-based and non-SLA factors based on the provider’s reputation and even financial status.

Rizvi et al. [22] utilized the auditor role to provide an objective trust baseline assessment to enable clients to decide between CP candidates. The proposal delegates the trust assessment to an auditor to calculate trust values. So that clients who need to choose between CPs request the trust values from the auditor
based on required service. The auditor role, we present, is not the same as the third party role in these works as shown in the trust establishment procedure 3. Hence the common trust management model in the Web relies on the binding a domain name and a public key, is not enough for privacy in cloud computing. A number of solutions were presented to enforce trust via technical means that ensure the privacy of the users data. Santos et al. 23 employed attribute-base encryption to provide a policy enforcement protocol based on Trusted Platform Module (TPM) abstraction. Similarly, Li et al. 17 proposed a model to support security duty separation in multi-tenant IaaS cloud between CP and customers based on TPM and they added the auditor role optionally. Moreover, Ge and Ohoussou 11 proposed to build an architecture for IaaS model to give the clients trust to deploy their VMs, that provides sealed storage and relies on remote attestation.

These models 23, 17, 11 were designed for Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) cloud models that require less security responsibilities on the CP 17 as they are shared with the customers, while SaaS model requires more responsibilities from CP 22.

A trustworthy and privacy-preserving cloud may be addressed by the use of cryptographic techniques such as fully homomorphic encryption (FHE) 12. However, it is still inefficient for most computations 24. Similarly in verifiable computing 21, it was designed to enable result correctness verification but has not shown support for general purpose cloud computing yet.

7 Conclusions and Future Work

We introduced the sealed computation concept and proposed a mutual checking procedure with an auditor role during setup time to provide an increased level of security and trust in cloud scenarios. The sealed computation concept abstracts from trusted hardware technologies like HSMs, the auditor is an abstraction of policies and procedures that increase trust in a single party.

We believe that the abstract system model using the auditor as an additional role is a good approach for medium-size and large cloud deployments instead of running their own private cloud. While the existence of the role of auditor may be intuitive, on the one hand, it is not clear whether the concept is really necessary, i.e., whether any technique that distributes trust can simulate the auditor as described above. On the other hand, practical methods for auditing could be investigated. Furthermore, we wish to attempt more rigid formalization for the attestation verification.

Acknowledgments

The authors would like to thank Nico Döttling, Johannes Götzfried, Tilo Müller and Hubert Jäger for hints and useful comments on earlier versions of this paper. This research is conducted under and supported by the “Privacy&Us” Innovative Training Network (EU H2020 MSCA ITN, grant agreement No.675730).
Bibliography

[1] Aazam, M., Khan, I., Alsaaffar, A.A., Huh, E.N.: Cloud of Things: Integrating Internet of Things and Cloud Computing and the Issues Involved. In: Applied Sciences and Technology (IBCAST), 2014 11th International Bhurban Conference on. pp. 414–419. IEEE (2014)

[2] Alam, S., Chowdhury, M.M., Noll, J.: SenaaS: An event-driven sensor virtualization approach for Internet of Things cloud. In: Networked Embedded Systems for Enterprise Applications (NESEA), 2010 IEEE International Conference on. pp. 1–6. IEEE (2010)

[3] Alhanahmah, M., Bertok, P., Tari, Z.: Trusting Cloud Service Providers: Trust Phases and a Taxonomy of Trust Factors. IEEE Cloud Computing 4(1), 44–54 (Jan 2017)

[4] Allianz Deutschland AG: Allianz BonusDrive User Guide. Webpage (2017), https://www.allianz.de/docs/auto/BonusDrive-UserGuide.pdf, accessed Jan 28, 2018

[5] Allianz press release: (in German) Nicht alle jungen Fahrer sind Straßenrowdies. Webpage (2017), https://www.allianzdeutschland.de/-nicht-alle-jungen-fahrer-sind-strassen-rowdies/-id_77853754/index, accessed Jan 28, 2018

[6] Baumann, A., Peinado, M., Hunt, G.: Shielding Applications from an Untrusted Cloud with Haven. In: 11th USENIX Symposium on Operating Systems Design and Implementation, OSDI ’14, Broomfield, CO, USA, October 6-8, 2014. pp. 267–283 (2014), https://www.usenix.org/conference/osdi14/technical-sessions/presentation/baumann

[7] Cloud Security Alliance: Security Guidance for Critical Areas of Focus in Cloud Computing v3.0. Tech. rep., Cloud Security Alliance (2011), https://downloads.cloudsecurityalliance.org/assets/research/security-guidance/csguide.v3.0.pdf

[8] Coker, G., Guttmann, J.D., Loscocco, P., Herzog, A.L., Millen, J.K., O’Hanlon, B., Ramsdell, J.D., Segall, A., Sheehy, J., Sniffen, B.T.: Principles of remote attestation. Int. J. Inf. Sec. 10(2), 63–81 (2011), https://doi.org/10.1007/s10207-011-0124-7

[9] Derikx, S., de Reuver, M., Kroesen, M.: Can privacy concerns for insurance of connected cars be compensated? Electronic Markets 26(1), 73–81 (2016), https://link.springer.com/article/10.1007/s12525-015-0211-0

[10] Dyer, J.G., Lindemann, M., Perez, R., Sailer, R., van Doorn, L., Smith, S.W., Weingart, S.H.: Building the IBM 4758 secure coprocessor. IEEE Computer 34(10), 57–66 (2001), https://doi.org/10.1109/2.955100

[11] Ge, C., Ohoussou, A.K.: Sealed storage for trusted cloud computing. In: 2010 International Conference On Computer Design and Applications. vol. 5, pp. V5–335–V5–339 (June 2010)

[12] Gentry, C.: Fully homomorphic encryption using ideal lattices. In: Proceedings of the 41st Annual ACM Symposium on Theory of Computing, STOC
[13] Georgiopoulou, Z., Lambrinoudakis, C.: Literature Review of Trust Models for Cloud Computing. In: 2016 15th International Symposium on Parallel and Distributed Computing (ISPDC). pp. 208–213 (July 2016)

[14] Habib Mahbub, S., Hauke, S., Ries, S., Mühlhäuser, M.: Trust as a facilitator in cloud computing: a survey. J. Cloud Computing 1, 19 (2012), https://doi.org/10.1186/2192-113X-1-19

[15] HUK-Coburg: (in German) Mit Sicherheit fahren und sparen unser Smart Driver Programm für junge Fahrer. Webpage (2017), https://www.huk.de/fahrzeuge/kfz-versicherung/smart-driver.html, accessed Jan 28, 2018

[16] Karapiperis, D., Birnbaum, B., Brandenburg, A., Castagna, S., Greenberg, A., Harbage, R., Obersteadt, A.: Usage-Based Insurance and Vehicle Telematics: Insurance Market and Regulatory Implications. Tech. Rep. 1, National Association of Insurance Commissioners (NAIC) (2015), CIPR Study Series

[17] Li, X.Y., Zhou, L.T., Shi, Y., Guo, Y.: A trusted computing environment model in cloud architecture. In: 2010 International Conference on Machine Learning and Cybernetics. vol. 6, pp. 2843–2848 (July 2010)

[18] Maene, P., Götzfried, J., de Clercq, R., Müller, T., Freiling, F., Verbauwhede, I.: Hardware-Based Trusted Computing Architectures for Isolation and Attestation. IEEE Transactions on Computers PP(99) (2017), https://dx.doi.org/10.1109/TC.2017.2647955

[19] Mell, P., Grance, T.: Effectively and Securely Using the Cloud Computing Paradigm. NIST, Information Technology Laboratory 2(8), 304–311 (2009)

[20] Morris Jr., J.H.: Protection in Programming Languages. Commun. ACM 16(1), 15–21 (1973), http://doi.acm.org/10.1145/361932.361937

[21] Parno, B., Howell, J., Gentry, C., Raykova, M.: Pinocchio: Nearly practical verifiable computation. In: 2013 IEEE Symposium on Security and Privacy, SP 2013, Berkeley, CA, USA, May 19-22, 2013. pp. 238–252 (2013), https://doi.org/10.1109/SP.2013.47

[22] Rizvi, S., Ryoo, J., Liu, Y., Zazworsky, D., Cappetta, A.: A centralized trust model approach for cloud computing. In: 2014 23rd Wireless and Optical Communication Conference (WOCC). pp. 1–6 (May 2014)

[23] Santos, N., Rodrigues, R., Gummadi, K.P., Saroiu, S.: Policy-Sealed Data: A New Abstraction for Building Trusted Cloud Services. In: Presented as part of the 21st USENIX Security Symposium (USENIX Security 12). pp. 175–188. USENIX, Bellevue, WA (2012), https://www.usenix.org/conference/usenixsecurity12/technical-sessions/presentation/santos

[24] Schuster, F., Costa, M., Fournet, C., Gkantsidis, C., Peinado, M., Mainar-Ruiz, G., Russinovich, M.: VC3: Trustworthy Data Analytics in the Cloud Using SGX. In: 2015 IEEE Symposium on Security and Privacy, SP 2015, San Jose, CA, USA, May 17-21, 2015. pp. 38–54 (2015), https://doi.org/10.1109/SP.2015.10
[25] Soleymanian, M., Weinberg, C., Zhu, T.: Sensor Data, Privacy, and Behavioral Tracking: Does Usage-Based Auto Insurance Benefit Drivers? Tech. rep., Sauder School of Business (University of British Columbia) & Krannert School of Management (Purdue University) (2017), https://news.ubc.ca/wp-content/uploads/2017/06/UBI_Paper_Latex_Marketing_Science-with-name.pdf

[26] Utimaco IS GmbH: Hardware Security Modules (HSMs) are the core business focus for Utimaco. Webpage (2018), https://hsm.utimaco.com/products/ accessed Jan 10, 2018

[27] Wagner, S., Krauß, C., Eckert, C.: Lightweight attestation and secure code update for multiple separated microkernel tasks. In: Information Security, 16th International Conference, ISC 2013, Dallas, Texas, USA, November 13-15, 2013. Proceedings. pp. 20–36 (2013), https://doi.org/10.1007/978-3-319-27659-5_2