Abstract

We develop the concept of Trusted and Confidential Program Analysis (TCPA) which enables program certification to be used where previously there was insufficient trust. Imagine a scenario where a producer may not be trusted to certify its own software (perhaps by a foreign regulator), and the producer is unwilling to release its sources and detailed design to any external body. We present a protocol that can, using trusted computing based on encrypted sources, create certification via which all can trust the delivered object code without revealing the unencrypted sources to any party. Furthermore, we describe a realization of TCPA with trusted execution environments (TEE) that enables general and efficient computation. We have implemented the TCPA protocol in a system called TCWasm for web assembly architectures. In our evaluation with 33 benchmark cases, TCWasm managed to finish the analysis with relatively slight overheads.

Keywords: Program analysis, regulatory property, trusted execution environment

1 Introduction

This paper offers a tentative solution to the following problem: vendor Alice wishes to sell executable software $E$ to clients such as Bob. Bob does not trust Alice and wants to examine the high-level design or sources behind $E$, but Alice is unwilling to do this to protect her intellectual property. In particular, the rapid growth of the international IT market, where IT products (e.g., software, hardware, services, etc.) are widely exported from one country to another has led to many such issues. Unfortunately, IT products are notoriously prone to bugs and security risks no matter in what forms they are deployed and in what environments they are running. Any vulnerable component in an IT product may cause a great loss to customers, e.g., national security threats, abuse of personal data, manipulation on digital asset, etc. In practice, the import and export of IT products are commonly required to be strictly compliant with local and international regulations. More importantly, such regulatory processes have to take place in a both trusted and confidential way, i.e., form a consensus on the regulatory compliance of an IT product among a group of relevant parties without leaking further sensitive information, e.g., source code, hardcoded values, etc. Figure 1 shows an illustrative example for further explanation.

Illustrative Example. We consider the case in which $B$ and $C$ have jointly developed software and exported it to $A$. As a service provider, $A$ imported the software to set up
a public service which further reached $D$ as a general user. Although this case is designed for explanation, it actually abstracts a typical scenario where nowadays IT products are deployed and used worldwide. Considering that the four participants may be from different countries, they are required to follow various regulations. For $B$ and $C$ as software exporters, they need to be compliant with local export regulations. For $A$ as a technology importer, his or her obligation is to check that the imported software introduces no regulatory risks, e.g., national security issues. From the perspective of $D$, his or her country might only allow the service to reach domestic users if it poses no threats to the public good, e.g., user privacy. In practice, it is hard to enforce the regulatory processes among these four parties due to the fact that the source code of the software is strictly confidential and therefore cannot be directly shared in a straightforward manner. Consequently, no single party in this case is able to believe that the software indeed delivers the required regulatory compliance across different countries.

**Trusted and Confidential Program Analysis.** To address this problem, we proposed a novel protocol in this paper to enable trusted and confident program analysis (TCPA) for checking regulatory compliance of software across multiple parties without mutual trust. More specifically, the proposed protocol guarantees that a) imported or exported software $E$ is indeed built from a given piece of secret source code $C$, b) both $E$ and $C$ are compliant with a set of mutually agreed regulatory properties $P = \{p_1, p_2, \ldots, p_n\}$, i.e., $E, S \models P$ and c) the compliance of $E$ and $S$ is verifiable without revealing sensitive information of $S$. Furthermore, we described a realization of TCPA called TCWasm using trusted execution environments (TEEs) and applied the system for analysis of web assembly (WASM) programs. In the preliminary evaluation with 33 benchmark files, TCWasm finished the analysis tasks with slight overheads of 139.3% and 54.8% in terms of time and memory usage, respectively; the baseline system executes the same analysis tasks without relying on TEEs. These overheads seem entirely acceptable to us given the added guarantees in terms of trust and confidentiality that the use of TEEs provides.

We summarize our main contributions below.

- We describe the problem of trusted and confidential program analysis and present a formalization of it to guide our subsequent research.
- We propose the first protocol to enable TCPA in practice, which is consistent with popular trusted computing technologies such as TEEs.
- We realize the protocol using AMD’s SEV TEE implementation. We develop the system TCWasm for verifying web assembly programs via TCPA; the first of its kind, to the best of the authors’ knowledge.
- We have conducted a large-scale evaluation of TCWasm and here report empirical evidence to demonstrate the feasibility of applying TCPA in practice.

**Paper Organization.** The rest of this paper is organized as follows. §2 introduces background information. §3 presents an in-depth explanation of the TCPA protocol. §4 describes the system design of TCWasm. §5 summarizes empirical results of the evaluation and §6 discusses related works. §7 concludes the paper.

2 Background

2.1 Trusted Computing

**Trusted computing** [28, 39] describes a number of technologies proposed to mitigate security threats. Unlike conventional passive approaches such as firewalls, malware detection, and intrusion detection, trusted computing takes a more active approach to addressing these threats, i.e., by establishing trust on a solid basis (typically referred to as the root of trust and implemented using both hardware and software) and then expanding this chain of trust to cover the entire computing system. Trusted Execution Environments represent arguably the most flexible and practical technology in this area. Some modern processors offer hardware primitives that support the execution of isolated computations, that is, the code and data they use are encrypted and integrity-protected. These TEE implementations are designed so that even the operator of the machine where such an execution takes place is unable to undetectably tamper with, or learn secrets manipulated by this execution. We use the terms TEE and TEE implementation interchangeably. Note that a TEE can be managing and executing multiple isolated computations concurrently. Examples of TEE implementations available are Intel’s Software Guard Extensions (SGX) [17], AMD’s Secure Encrypted Virtualization (SEV) [48], and ARM’s TrustZone [41]. Each of them is designed to address different application scenarios, but they all share similar core capabilities. We introduce some of these common building blocks as follows.

These implementations rely on special instructions to load the isolated computation’s code and data, in encrypted form, into the main memory, while measuring them in the process, and execute it. They isolate computations at different levels of granularity. For instance, while AMD SEV isolates an entire virtual machine (VM), Intel SGX isolates part of a (operating-system) process. This measurement and the encrypted memory pages are created, managed, and protected by the TEE. The attestation process plays a key part in establishing the chain of trust. Roughly speaking, it generates cryptographically-protected evidence attesting that a computation with a given measurement has been properly isolated; it also attests the authenticity of the TEE implementation - hardware and software components - and its capabilities. By properly verifying this evidence, an entity interacting with
this computation can be confident of its isolation and, consequently, of the guarantees that follow. We detail this process later. For instance, in the case of AMD SEV, the attestation process can be used to establish that a VM has been properly set up by checking the boot process and the elements it depends upon have the expected measurements, i.e. OS image, installed programs and data, etc. The isolation offered by TEE implementations is restricted to the main memory. The developer of the isolated computation is responsible for encrypting data on disk.

2.2 Program Analysis

In general, program analysis develops on methods and technologies at establishing the relationship between a given software program and expected properties, e.g., correctness, robustness, safety, and liveness. Typical program analysis tasks are program optimization, vulnerability detection, and formal verification. Considering the approaches taken, program analysis technologies can be categorized as static program analysis, dynamic program analysis, and both in combination. Static program analysis technology finishes its task by not running or executing the target program. Common static program analysis methods are control-flow analysis, data-flow analysis, abstract interpretation, type analysis, and pointer analysis. All of these methods first model the given program and its expected property abstractly as a set of mathematical constraints, for which the analysis task boils down to establishing satisfiability. In contrast, dynamic program analysis fulfills its goal by examining actual runs of the target program and checking for the expected properties. Fuzzing, symbolic execution, and runtime monitoring are among the most frequently used dynamic program analysis technologies. While static and dynamic program analysis have their strengths in efficiency and precision, respectively, neither of them is able to tackle all real-world problems. Thus, there is another category of hybrid program analysis technologies which combines both approaches. TCPA encompasses all of these.

3 Protocol For TCPA

3.1 Overview

The general workflow of TCPA is shown in Figure 2. The protocol defines the following types of actors, namely, Provider (Alice), Consumer (Bob), and the Trusted and Confidential Program Analysis Isolated Computation (TCPA-IC). Alice is the software provider in this setting who wants to export her products to the Consumer Bob and therefore needs to convince him that the exported software is strictly compliant with regulations. As aforementioned, Alice also needs to avoid revealing the product’s business secrets (e.g., source code) to non-relevant parties such as Bob. In this set-up, Bob hosts the TEE where TCPA-IC is to be executed. He is in charge of setting up the TEE-enabled platform and TCPA-IC. Even with unlimited access to the platform, not even Bob can infer any secrets from this compliance analysis since the product is analysed within the isolated service TCPA-IC. Of course, we could have an alternative setup where Alice or a third party would host the TEE where TCPA-IC executes. This set-up, however, reinforces and highlights that even the platform’s operator, with unrestricted access, cannot read into the isolated computation’s execution.

Important concepts in TCPA as listed below.

- $S$ is the source code of a given piece of software.
- $E$ is the executable corresponding to $S$.
- $P = \{p_1, p_2, \cdots, p_n\}$ is a set of regulatory properties to be checked.
- $X$ is a program analysis framework, e.g., static analysis, dynamic analysis.
- $B$ is the building framework of $S$, i.e., create $E$ from $S$. The most common example of $B$ is a compiler.
- TCPA-IC$(X, B, P)$ is the isolated computation that carries out the indicated trusted and confidential program analysis.
- Public and private keys $IC_{pub}$ and $IC_{priv}$, respectively, are elements of a signature scheme used to authenticate messages issued by TCPA-IC$(X, B, P)$.
- $T$ is a symmetric key for encryption and decryption. $S_T$ indicates an encrypted version of $S$.
- The platform certificate ($PC$), isolated computation certificate ($ICC$), and compliance certificate ($CC$) attest the platform’s capabilities, the isolated computation’s measurement, and the program analysis’ outcome, respectively - we detail these elements in the following.

3.2 Platform set-up

Before the protocol in Figure 2 can be executed, we assume a platform setup step; omitted from that figure for the sake of simplicity. In this step, the platform engage in a protocol with the processor manufacturer, who is typically also the TEE implementer, aimed at proving the processor’s authenticity, its capability to run isolated computations, and that all the trusted elements - both hardware and software - part of the TEE implementation are valid and have been properly set up. Manufacturers store a non-exportable secret in the chip’s fuses that allows them to authenticate processors. Once a chip is authenticated and its capabilities checked, low-level primitives can be trusted to correctly validate hardware and software components of the TEE implementation. As a result of this process, the processor’s manufacturer issues a platform certificate ($PC$) - we describe this certificate and its elements as follows.

- The manufacturer’s public and private root of trust keys $RoT_{pub}$ and $RoT_{priv}$, respectively, are elements of a signature scheme used to authenticate messages issued by this actor. The public component is well-known and trusted to be the correct root of trust key for the manufacturer.
The initialization phase of TCPA begins with Producer and Consumer agreeing on the program analysis framework $X$, building framework $B$, and regulatory properties $P$ that are to be used by our isolated computation $TCPA-IC$. Once they have agreed on these parameters, Bob creates the isolated computation $TCPA-IC(X, B, P)$ as he is the owner of the platform. Thus, the code and data used by $TCPA-IC(X, B, P)$ is loaded in encrypted form, measured, and executed. Once this service starts, it generates its own key pair using a trusted source of randomness, and the isolated computation certificate (ICC). We define these elements as follows.

- The TCPA-IC ($X, B, P$) public and private keys $IC_{pub}$ and $IC_{priv}$, respectively, are elements of a signature scheme used to authenticate messages issued by this actor. These keys are managed by the TEE implementation and not even the platform owner has access to the private components.
- $PC = (Plat_{pub})_{RoT_{priv}}$ is a certificate containing the platform’s protected public key and a cryptographic signature of this key issued by the processor’s manufacturer using $RoT_{priv}$.

This certificate is evidence that the platform’s TEE is valid and has been properly set up, and its authenticity can be verified using $RoT_{pub}$. It also vouches for the platform protected key $Plat_{pub}$. As we detail later, this certificate and the elements above play a part in the attestation process.

As shown in Figure 2, the protocol works in three phases, i.e., initialization, remote attestation and program analysis. We now describe them in detail.

### 3.3 Initialization

The initialization phase of TCPA begins with Producer and Consumer agreeing on the program analysis framework $X$, building framework $B$, and regulatory properties $P$ that are to be used by our isolated computation $TCPA-IC$. Once they have agreed on these parameters, Bob creates the isolated computation $TCPA-IC(X, B, P)$ as he is the owner of the platform. Thus, the code and data used by $TCPA-IC(X, B, P)$ is loaded in encrypted form, measured, and executed. Once this service starts, it generates its own key pair using a trusted source of randomness, and the isolated computation certificate (ICC). We define these elements as follows.

- The TCPA-IC ($X, B, P$) public and private keys $IC_{pub}$ and $IC_{priv}$, respectively, are elements of a signature scheme used to authenticate messages issued by this actor. These keys are managed by the isolated computation process $TCPA-IC(X, B, P)$ and not even the platform owner has access to the private components.
- $ICC = (m_{IC}, IC_{pub})_{Plat_{priv}}$ is a certificate containing the cryptographic measurement of the isolated computation process $TCPA-IC(X, B, P)$ given by $m_{IC}$, and $TCPA-IC(X, B, P)$’s public key $IC_{pub}$. The certificate is signed by the platform’s protected private key $Plat_{priv}$. The measurement $m_{IC}$ is a cryptographic hash of the memory pages, i.e., code and data, loaded into main memory corresponding to $TCPA-IC(X, B, P)$; it accounts for the parameters $X$, $B$ and $P$.

This certificate provides evidence that an isolated computation with measurement $m_{IC}$ has been created by a platform identified by key $Plat_{pub}$, and that this computation certified the blob of data, which happens to be its public key, $IC_{pub}$. While the measurement of the computation is calculated and set by the TEE, the isolated computation is free to pass any extra blob of data to be certified. Thus, while the
measurement can be trusted to be correct, provided that the platform and TEE are trusted, the blob of data must only be relied upon if the isolated computation’s code request the certification of the appropriate data.

### 3.4 Remote Attestation

The remote attestation process should provide enough evidence to convince Alice (Provider) that the expected isolated computation has been properly set up and started in a valid TEE-enabled platform. This phase begins by Alice requesting both the platform and isolated computation certificates PC and ICC. Once she receives them, Alice can verify this attestation certificate chain. She knows and trusts the manufacturer’s RoT_{pub} key. Therefore, she can use this key to verify PC’s signature/authenticity. Once this certificate is verified, she can extract the platform protected key Plat_{pub} from it and use this key to verify ICC. The last step in this verification process consists of checking for the expected measurement. Alice calculates the measurement that she expects for TCPA-IC(X, B, P) - let us call it m_{exp} - and then compares it to the m_{IC} element of ICC. If any of these verifications fail, Alice stops taking part in the protocol. If all of them succeed, however, Alice should be convinced that TCPA-IC(X, B, P) has been correctly isolated, it is the computation expected, and, as part of its execution, its public key I_{C_{pub}}, an element of certificate ICC, has been certified.

In the final step in this phase Alice and TCPA-IC(X, B, P) negotiate T: a symmetric encryption scheme key used to confidentially transmit data between them. This key is negotiated in a way that it does not become known to Bob, say using some form of the Diffie–Hellman key exchange method. The key pair I_{C_{pub}} and I_{C_{priv}} can be used to authenticate TCPA-IC(X, B, P)'s messages in this negotiation process.

### 3.5 Program Analysis

The program analysis phase of our protocol involves the examination of S and E. Alice starts this phase by sending S_{T} and E to TCPA-IC(X, B, P). The isolated computation, then, decrypts S_{T} and proceeds to check: (i) whether S meets the properties P, and (ii) whether E is an executable capturing the behaviour of S. In principle, TCPA does not limit the type of analysis run by TCPA-IC, that is, any well-defined framework could be used to verify S’s compliance with P and E's correspondence to S. Figure 3 illustrates a framework to check both (i) and (ii). The left part demonstrates a typical analysis flow based on symbolic execution. The source code of a program is firstly taken by CFG builder to generate a control flow graph, i.e., CFG. Then, a symbolic execution engine is triggered to explore the CFG with symbolic inputs. In the process of symbolic execution, symbolic traces are produced for further analysis. For a specific trace, a semantic analyzer checks whether the properties hold or not. Lastly, an analysis report is generated as a summary of the process. The design of a specific program analysis technique is not our main focus in this paper, and as mentioned before, other verification frameworks could be plugged into our TCPA protocol. The right part of this framework describes a process to determine E’s correspondence to S. Specifically, an executable E’ is built with B for the given S. Then, E’ is compared with E (i.e., executable provided by Alice) using an executable checker that syntactically compares them for equality. If so, it is safe to conclude that E corresponds to S. Of course, we could have more sophisticated executable checkers where some form of semantic equivalence between E and E’ could be checked instead. Furthermore, we could even completely bypass this comparison step, and return E’ to Alice. Given that this executable was created by TCPA-IC(X, B, P) using B and that B is trusted to be correct, E’ should correspond to S. Once the analysis is finished, TCPA-IC(X, B, P) creates the compliance certificate (CC) as follows.

- CC = (h(S), E, R)_{I_{C_{priv}}}, contains a cryptographic hash of S (i.e., h(S)), the executable E sent by Alice, and an analysis report R, and it is signed using the computation TCPA-IC(X, B, P)'s private key I_{C_{priv}}. The report R is a pair of (eo, (po_1, …, po_n)) where eo is the executable equality outcome - a boolean that is true if they are equivalent, and false otherwise - and the tuple (po_1, …, po_n) has a property verification outcome po_i for each corresponding to property p_i in P. The format of property outcomes po_i will vary based on the choice of source code and property languages, and verification framework. For instance, considering stochastic systems and verification frameworks, a property outcome would present the likelihood of a property being valid. On the other hand, a non-stochastic model checker applied to a deterministic program could output precisely whether a property holds. There are even non-stochastic approximate analysers which might admit an unknown outcome when they cannot issue a definitive statement about the specific S and p_i being analysed. These approximations are typically used for the sake of decidability or efficiency. Finally, CC is sent back to Alice which can forward PC, ICC and CC to Bob. He can then verify this certificate chain.
just like Alice does on the remote attestation phase with the extra steps that CC’s signature must be verified against \(c_{pub} \) and that the report \(R \) in CC must have the executable equality outcome set to true and that all properties are valid. If the verification of this certificate chain succeeds, Bob trusts \(R \) and, consequently, the compliance status of \(E \) - and can start using this product.

In this protocol, neither Alice or Bob authenticate any messages by, say, signing them. We could, of course, require that Alice and Bob have a key pair each, for which public component is known to the other participant, that they could use to set up authenticated and confidential channels between them using well-known cryptographic protocols. The protocol could then take place over these channels. We do not detail this set-up as our primary goal in this paper is to introduce a protocol by which Bob can be convinced of \(E \)'s (and \(S \)') compliance without having access to \(S \) and not make it confidential to other parties.

Perhaps one interesting addition to the protocol would be a certificate of origin provided by Alice. In the current version of the protocol, Bob can verify that \(E \) meets the expected regulatory properties, but the protocol does not have any mechanism to tie \(E \) and \(S \) to Alice. Of course, Bob might be satisfied that \(E \) complies with \(P \) alone, regardless of who the author of \(E \) or \(S \) is. However, Bob could also demand to know their author so that he can later raise a dispute related to \(E \) against its author, for instance. To satisfy this demand, the protocol could be extended with an extra step by which Alice generates an origin certificate \((OC)\) containing the \(h(S)\) and \(E\), and cryptographically signed by its private key \(A_{priv}\) - the public counterpart \(A_{pub}\) of which is known to Bob. This certificate attests Alice’s authorship and can be verified by Bob using \(A_{pub}\). This certificate together with \(h(S)\) in CC commits Alice to the source code used in TCPA. Thus, she cannot claim a different source code was used by the protocol in a possible dispute resolution process.

Note that, as the platform owner/TEE host, Bob has unrestricted access to the messages transiting between Alice and TCPA-IC\((X, B, P)\), and to the platform and TEE running this isolated computation, and yet he is unable to learn anything about the source code \(S\) apart from its compliance status with respect to properties \(P\) and that it gives rise to executable \(E\). He does not have access to the source code when sent by Alice to TCPA-IC\((X, B, P)\) as the negotiated symmetric key \(T\) is not known to him, and the TEE managing the execution and isolation of TCPA-IC\((X, B, P)\) prevents him from accessing this secret when its compliance analysis is being carried out.

Regulators may also impose restrictions on the verification framework \(X\) used to verify whether \(S\) meets \(P\). They could, for instance, have a list of approved frameworks, and expect only those to be used in the context of TCPA-IC. The measurement of TCPA-IC\((X, B, P)\) - which depends on \(X\), \(B\), and \(P\) - can be used to show that an approved framework has been indeed used. A party using our protocol ought to be able to independently calculate the measurement of TCPA-IC\((X, B, P)\), given \(X\), \(B\), and \(P\), for the sake of confirming it is interacting with the appropriate isolated computation in the process of remote attestation. Therefore, it can use this trusted measurement to test if a given framework \(X'\) was used and, then, check whether \(X'\) is in the list of approved frameworks. More sophisticated procedures could be devised to ensure a given verification framework meets the norms of a regulator, including having its code verified for some properties using perhaps its own separate TCPA-IC instantiation for that.

It is worth mentioning that verification frameworks can be non-deterministic, that is, for some frameworks, two executions checking the same system and property can give rise to different verification outcomes. The parties relying on our protocol must keep this sort of behaviour in mind as it can be maliciously exploited. Let us say, for instance, that a verification framework in very rare occasions fail to report that a property is violated, returning that it was unable to assert the property instead, and let us assume that this sort of unknown result is good enough to pass some regulation. This sort of behaviour could be explained, for instance, if we had a verifier \(X'\) that has a constraint on the number of states it can examine, and so, for a given input system \(S'\), a large randomly-selected portion of its state space can be analysed but not all of it. In such a case, a malicious party could re-analyse \(S'\) using our protocol until \(X'\) misses the small fraction of states of \(S'\) that witness the violation. Thus, the consumer \(B\) might then need to know that the TCPA analysis is instigated by someone he trusts such as \(B\) himself - as it is in the detailed protocol we have set out. Program analysis typically produces reports in addition to a yes/no/unknown result. In TCPA, the form of a report, e.g., an exception leading to a counter example, may need to be withheld from the software customer because it gives away details of the confidential sources.

4 Design of TCWasm

4.1 Architecture

We realized the TCPA protocol as described above in the TCWasm system to enable trusted and confidential program analysis for programs that compile to web assembly (WASM). Specifically, we used the AMD SEV [48] as the underlying trusted execution environment and a symbolic-execution-based engine to deliver program analysis [54]. The architecture of TCWasm is shown in Figure 4.

In general, TCWasm is implemented as a form of cloud service and is compatible with any existing platform, e.g., Amazon, Google, Alibaba etc. We offer four types of sub-services for end users, e.g., Alice and Bob in Figure 2, who are trying to agree on the regulatory compliance of a confidential software. The functionalities of these sub-services are summarized below.
Figure 4. The architecture of TCWasm.

- **Regulatory Property Service** allows a software customer to publish an agreed set of regulatory properties which will be verified for the software created by a provider later in TCWasm. The agreement on properties is formed with signatures of both the provider and customer included. The service also offers accesses to properties that are publicly available. Any relevant participant - e.g., downstream users, audit teams, etc - can check the properties managed on TCWasm and understand the compliance guarantee from their own perspective.

- **Program Analysis Service** runs the underlying analysis processes to decide whether the given software is compliant with the specified set of properties. As illustrated in Figure 2, the provider is required to submit an encrypted version of source code and the deployed executable. The service will generate a certificate of compliance as a form of report for relevant parties, e.g., the customer, to confirm that the specified computation process has been executed on the given software and yielded a compliance decision for it to explain whether the software satisfies the properties, and why it is the case.

- **Configuration Service** helps users configure TCWasm based on their preference. Practically, it is reasonable to make the projection that TCWasm will probably have a collection of program analysis settings instead of a single one. For example, different customers might like to adopt different algorithms to analyze the software. The configuration service allows users to specify the computation without looking into too many technical details.

- **Remote Attestation Service** enables an end user to verify the running environment on the cloud. To this end, a user is required to post a request to TCWasm and start the remote attestation process. The service sends back a cryptographic certificate to guarantee that the running environment is indeed as stated (e.g., an AMD SEV) and the image to be loaded and executed is as expected. The certificate can be passed to other parties and they can then confirm the validity of the running environment by checking the certificate. The remote attestation service can be contacted at any time during the execution to generate the certificate as long as it is necessary to do so.

### 4.2 Trusted Environment

We use AMD SEV as the underlying TEE environment for TCWasm. A cryptography library is included to realize encryption and decryption actions as specified in TCPA based on the set of cryptographic keys provided in AMD SEV. In addition, TCWasm implements a set of APIs to deliver the trusted certificate from AMD SEV to end users, e.g., a verifiable measurement of firmware, disk, memory, etc. Due to the portability of AMD SEV, integration with other program analysis engines is straightforward.

### 4.3 Property Specification and Management

In TCWasm, the agreed set of regulatory properties is stored on a blockchain. Therefore, a majority of nodes in the network will have a consistent view on those properties as they replicate the ledger and states. To this end, TCWasm embeds a blockchain client to interact with the underlying blockchain. In principle, both permissioned and permissionless blockchains can fit in our setting, e.g., Ethereum [53], Fabric [10], etc. While the former is more suitable for a relatively stable group of software providers and customers, the latter fits better in an open market where any global participant is allowed to join. The blockchain client can submit
properties provided by users to blockchain in several different ways, e.g., as transaction metadata, as structural storage of smart contracts, etc. In cases of dispute (i.e., providers and consumers have conflicting views on properties) which is commonly resulted from forking on the blockchain, TCWasm is able to have a further decision after several blocks and the longest chain can be identified.

Moreover, properties can be defined with both existing or user-defined specification languages, e.g., computation tree logic, linear temporal logic, etc. In the preliminary realization of TCPA, we specify safety properties as program assertions, e.g., via assert statement. Therefore, the checking of such properties is converted to a reachability problem where an analysis is required to search for a transition that can potentially lead to an unsafe state. As mentioned earlier, it is possible to have multiple types of specifications in TCWasm. Users are allowed to configure which one they will apply for the submitted properties.

4.4 A Formal Framework For Analyzing WASM

We formalize a WASM program \( P := \langle M_0, M_1, \cdots, M_n \rangle \) as a group of modules to be deployed, each of which is a tuple \( M_i := \langle T, F, T, M, G \rangle \), where

- \( T \) defines a vector of function types.
- \( F := \langle F_0, F_1, \cdots, F_n \rangle \) is a collection of functions. For each function \( f \in F \), \( f = \langle f \in T, L, E \rangle \) comes with a type, a set \( L \) of local variables that are only accessible inside a function and a list \( E \) of expressions. More specifically, expressions in \( E \) are converted to a control flow graph, where a node in the graph is a basic block that includes a sequence of WASM statements and an edge is a jump from one basic block to another.
- \( T \) is a table of indexed function references.
- \( M \) is a list of memory elements which can be linearly addressed inside a module.
- \( G \) is a set of global variables which can be accessed from any function.

The program analysis framework \( A \) that we developed in this work for WASM programs is formalized as a tuple \( A := \langle K_f, K_o, \text{SrcMap}, \text{Spec} \rangle \), where \( K_f \) and \( K_o \) are stacks of function calls and operands, respectively. \( M \) denotes the set of modules to be analyzed by \( A \). \text{SrcMap} is a source map which creates a bidirectional link between confidential source code and bytecode of WASM. \text{Spec} is the specification standard of WASM. Moreover, a configuration of \( A \) is abstracted as \( c := \langle pc, src, k_f, k_o, S, P, G \rangle \), where

- \( pc \) is a program counter that points to the current program location.
- \( src \) is a source code pointer which maps from current \( pc \) to the corresponding source code (e.g., at a specific line of code and offset).
- \( k_f \) shows the current stack of functions.
- \( k_o \) describes the current stack of operands.

As introduced above, the current implementation of program analysis in TCPA is based on symbolic execution. Specifically, the configuration of \( A \) is initialized with a starting module \( M_i \) and function \( f_k \). The analysis start by examining the statements in this function’s body. Given a statement \( e \), the program analysis framework \( A \) retrieves elements from \( K_o \), performs computation as specified in the WASM standard, potentially updating memory, local storage, global storage, path conditions and semantic graph. That said, the processing of \( e \) yields a transition of configuration of \( A \), from the current one \( c := \langle pc, src, k_f, k_o, S, P, G \rangle \) to a new one \( c' \). When a program path has been visited, we combine the path conditions with the specified properties for SMT solving and further verifying whether the properties hold or not. This process iterates until a completion criterion for program analysis is realized, e.g., coverage, time, etc.

Although symbolic execution is performed on WASM bytecode, it requires fundamental knowledge from the confidential source code. The most obvious information required in TCPA is a source map that links every bit in the bytecode back to source code, and the other way around as well. With a source map, TCPA can provide software producers with understandable results, e.g., a bug is located at a specific line. Moreover, type information at source code level is also important to facilitate program analysis. For example, we would be able to associate memory access with variables in source code with their types.

The analysis framework \( A \) can have different implementations. As Figure 4 shows, we currently use a framework based on symbolic execution but the general design can fit into a wider range of program analysis techniques, e.g., formal verification, automated testing, etc.
5 Preliminary Evaluation

5.1 Benchmark and Evaluation Setup

**Benchmark.** We have conducted a preliminary evaluation of TCWasm. The benchmarks used in the evaluation are shown in Table 1. We used 8 examples from different application domains with 33 web assembly files in total. The size of benchmark files varies from 2KB to 840KB. We also counted the number of WASM instructions in all files, which manifested a relatively large difference across different test cases. The largest one (Zxing) has over 381K instructions, while the smallest (Snake) only includes 528 instructions. The benchmarks and results are publicly available at http://omitted.for.double-blind-review/.

**Evaluation Setup.** All the experiments were performed on two environments, *i.e.*, with and without TEE, respectively. The TEE environment was set up on Google Cloud confidential computing platform\(^1\), which uses the AMD Epyc processor and SEV-ES\(^2\) as the underlying TEE setting. The cloud machine was configured with dual 2.25GHz cores, 8GB memory and a Ubuntu 18.04 operating system. Moreover, the non-TEE environment carried Intel i9 processor with dual 2.3GHz cores, 8GB memory and a Ubuntu 18.04 operating system. All the computation was executed by only one core of the processor in our evaluation.

5.2 Evaluation Results

In the evaluation, we ran TCWasm with and without the support of TEE (*i.e.*, AMD SEV in our case) on all benchmarks. For a test file \(f\), TCWasm performs a systematic program analysis based on symbolic execution [33] to explore the state space of \(f\) and create a semantic abstraction as well. That said, the execution did not include detection of specific types of bugs or errors, as in many existing program analyzers. The goal of this evaluation was to understand the performance trade-off with the design of TCPA, rather than assessing the effectiveness of a certain bug-detection algorithm. With a framework such as TCWasm, the implementation of a detector is a straightforward task even in the context of TCPA.

**Time Overhead.** The time cost with and without a TEE is described in Table 2. In the evaluation, we observed the smallest 7.7% overhead in the case of tfjs-backend, while the largest case was 367.5% for imagequant. The average time overhead was 139.3% on all benchmark files. For a subset of the test cases, files with larger sizes introduced bigger time overhead as expected. For instance, binjgb, module1, avif_dec led to an increasing level of overhead with a growing size and number of instructions. However, there were exceptions in the evaluation where big files manifested small overheads. For example, in the case of mozjpeg_enc (217 KB), running TCWasm is 95.1% slower than the non-TEE version.

For the case of rotate (14 KB) which is only 6.5% as large as mozjpeg_enc, the overhead was 107.0% that amounts to a relative 12.5% growth. Further discussions on root causes of the overhead can be found below.

**Memory Overhead.** In addition to time cost, we analyzed the memory overhead with TCWasm in our evaluation. Similarly, the analysis was conducted with and without the support of TEE, as shown in Table 3. In general, majority of the overheads were below 45%. More specifically, the overheads for half of the test cases were even less than 8%, which we believe is highly acceptable in practical scenarios. On the other hand, there were two cases that manifested a 2X and 4X overheads, although the actual memory used were not big, *i.e.*, 10.8MB and 36.4MB respectively. The tfjs-backend file was particularly interesting due to the fact that TCWasm consumed less memory with a TEE than the non-TEE version. Detailed explanations are given in the following section.

5.3 Discussions

We now describe a further discussion on the empirical results with TCWasm to help understand its performance manifested in the evaluation.

**General Explanation.** First of all, the runtime overheads in general introduced by TCWasm in our evaluation are easy to understand. In the case of time overhead, the execution of TCPA protocol was encapsulated in a TEE environment, which encrypts and decrypts memory accessed by the running program, *i.e.*, in our case the TCWasm implementation, therefore should last longer than running TCPA without a TEE (139.3% as described in Table 2), depending on how efficient the TEE is realized. On the other hand, TCWasm did not manifest a higher level of memory consumption than a non-TEE implementation for the majority of test cases used in the evaluation as shown in Table 3, due to the fact that encryption and decryption of memory in a TEE are not memory-intensive procedures thus commonly require little extra memory in running TCPA.

**Special Cases.** Despite the general analysis of evaluation results, we did observe that there were exceptions that seemed not to be consistent with other cases. As shown in Table 2, it was much slower for TCWasm to process avif_dec, imagequant and asm-dom than other test files. The average time overhead for the three is 273.0% which almost doubles the number of total average. As explained above, the time overhead is mainly resulted from encryption and decryption of memory used by TCWasm. More specifically, the overhead is closely correlated to the memory complexity of analysis (*e.g.*, the amount of memory used and the frequency to access it) adopted in the TCPA realization, *i.e.*, a symbolic-execution based analysis. Like many other well-designed symbolic engines, TCWasm uses a variety of specific data structures to store intermediate information of program analysis, *e.g.*,...
Table 1. Statistics of the benchmark. KB: kilobyte.

| Type              | Benchmark | File     | Size (KB) | #Instruction |
|-------------------|-----------|----------|-----------|--------------|
| Image Processing  | Squoosh   | module1  | 224       | 111,533      |
|                   |           | avif_dec | 640       | 152,481      |
|                   |           | imagequant | 58        | 26,641       |
|                   |           | mozjpeg_enc | 217      | 64,426       |
|                   |           | rotate   | 14        | 700          |
|                   |           | zxing    | 840       | 381,368      |
| Machine Learning  | Tensorflow | tfjs-backend | 222      | 108,735      |
| Library           | C Standard Library | stdio | 11        | 5,156        |
|                   |           | string   | 11        | 4,664        |
|                   |           | memory   | 16        | 8,519        |
| Framework         | asm-dom   | asm-dom  | 100       | 44,828       |
| Game              | Game Boy  | binjgb   | 98        | 41604        |
|                   | Maze      | maze     | 2         | 780          |
|                   | Snake     | snake    | 2         | 528          |

Table 2. Time cost. s: second.

| File     | TEE (s) | Non-TEE (s) | Overhead |
|----------|---------|-------------|----------|
| module1  | 67.7    | 36.3        | 85.4%    |
| avif_dec | 1,823.6 | 559.6       | 225.9%   |
| imagequant | 493.0   | 105.4       | 367.5%   |
| mozjpeg_enc | 659.7   | 338.2       | 95.1%    |
| rotate   | 358.4   | 173.1       | 107.0%   |
| zxing    | 1,427.5 | 530.4       | 169.3%   |
| tfjs-backend | 712.9   | 661.1       | 7.7%     |
| stdio    | 53.5    | 20.4        | 162.3%   |
| string   | 26.5    | 10.5        | 152.4%   |
| memory   | 117.9   | 46.0        | 156.3%   |
| asm-dom  | 382.5   | 117.5       | 225.5%   |
| binjgb   | 155.5   | 136.7       | 13.8%    |
| maze     | 2.2     | 1.0         | 120.0%   |
| snake    | 0.5     | 0.3         | 61.3%    |
| average  |         | *           | 139.3%   |

Table 3. Memory cost. MB: megabyte.

| File     | TEE (MB) | Non-TEE (MB) | Overhead |
|----------|----------|--------------|----------|
| module1  | 6.4      | 5.7          | 12.3%    |
| avif_dec | 80.2     | 59.5         | 34.8%    |
| imagequant | 51.2    | 10.8         | 374.1%   |
| mozjpeg_enc | 78.5    | 75.9         | 3.4%     |
| rotate   | 15.7     | 14.8         | 6.1%     |
| zxing    | 106.0    | 36.4         | 191.2%   |
| tfjs-backend | 65.4    | 65.6         | -0.3%    |
| stdio    | 11.7     | 10.9         | 7.3%     |
| string   | 6.1      | 5.7          | 7.0%     |
| memory   | 15.2     | 14.2         | 7.0%     |
| asm-dom  | 52.3     | 49.4         | 5.9%     |
| binjgb   | 20.6     | 14.2         | 45.1%    |
| maze     | 2.8      | 2.0          | 40.0%    |
| snake    | 0.8      | 0.6          | 33.3%    |
| average  |         | *            | 54.8%    |

states of analysis, symbolic contexts, path conditions, etc. Particularly, TCWasm introduced a graph-based structure to separate the modeling of a given program and its symbolic execution process. While the advantage of such design is to have better composability via integration with different symbolic execution engines and backend analyzers, it inevitably increases the level of memory consumption and access frequency. Moreover, abnormal time overheads were partially attributed to the evaluation setting as well. We use an illustrative example in Figure 5 to explain the cause.

Figure 5 describes an evaluation setting to cover two paths in the given program and the exploration of each path is bounded within a specified timeout, e.g., one second. Although settings may vary across different program analyzers to deal with specific use cases, they commonly share similar fundamental parameters, e.g., level of coverage and timeout for SMT solving. In particular, Figure 5 demonstrates a scenario where setting overhead is introduced. Specifically, a program analyzer without TEE (left) manages to cover the first and second paths of a given program and then finishes the analysis without exploring the remaining paths. However, in the case on the right, the program analyzer with TEE (right) manages to cover the first path of a given program, fail at the second and third due to timeouts of SMT solving, and then cover the last. In such cases, although overheads on two visited paths are relatively small, the total overhead becomes much bigger because of unfinished explorations on the other two paths.
Table 4. The preliminary performance validation with simple programs.

| File               | Time (second) | Memory (MB) |
|--------------------|---------------|-------------|
| self_addition      | 14.2          | 0.7         |
| array_addition     | 3.6           | 0.8         |
| quick_sort         | 134.4         | 32.4        |
| constraint_addition| 0.4           | 0.3         |
| constraint_division| 5.0           | 2.6         |

In terms of memory overhead, the evaluation manifested abnormal results as well. Specifically, imagequant and zxing introduced a large overhead while tfjs-backend even showed a negative overhead, i.e., TCWasm was faster than the non-TEE version. Commonly, TCPA does not introduce a high level of memory overhead because the encryption process, e.g., AES as used in our case with AMD SEV, often generates ciphertexts with similar sizes as plaintexts. However, there might be cases as well where ciphertexts are bigger with specific padding strategies. Another factor to potentially affect the measurement of memory overhead is garbage collection in virtual machines. For cases where memory consumption is measured right after a garbage collection process, we might have a much smaller number than expected. Further investigation on such cases is left as future work.

Figure 5. An evaluation setting of covering two paths with a specified timeout on each path.

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**Preliminary Validation.** Since the implementation of TCWasm is non-trivial, we conducted a preliminary validation with a small group of simple test cases to justify the root cause analysis as described above. The validation is shown in Table 4.

Specifically, the test cases used in the validation included the following programs:

- **self_addition**: increment a variable $10^7$ times with a specific value
- **array_addition**: add to $10^7$ elements in a given array
- **quick_sort**: quick sort a given list
- **constraint_addition**: a program with an addition constraint for SMT solving
- **constraint_division**: a program with a division constraint for SMT solving

As shown in the first two rows of Table 4, self_addition manifested a relatively lower level of time overhead (13.6%) compared to array_addition (350.0%). The gap is resulted from different structures of memory accessed by both programs. While self_addition only manipulated a single unit of memory, array_addition is allocated with a consecutive memory space therefore each access to it requires addressing with the starting point and the offset. As a result, running array_addition with TEE was much slower than without TEE due to encryption of a more complicated memory. In the case of self_addition, TEE did not slow down too much of the execution. Furthermore, a similar explanation can apply to quick_sort, i.e., the third row of Table 4. Since the memory used by a quick sorting algorithm commonly includes a pivot and sub-lists of a given list, it introduced a high level of time overhead (314.8%) as array_addition. Moreover, the last two rows of Table 4 demonstrated two cases with simple and complicated path constraints for SMT solving, respectively. While constraint_addition generated a constraint with addition, constraint_division was a division constraint. Therefore, it took longer for TCWasm to solve constraint_division than constraint_addition. As explained in Figure 5, TCWasm managed to solve the division constraint without TEE but failed with TEE due to timeout (which could be verified based on runtime logs). Therefore, the time overhead in the forth row is larger, i.e., 92.3%. On the other hand, the addition constraint can be solved with and without TEE thus did not manifest a large overhead in the last row. In terms of memory, all cases introduced slight overheads, which can be explained by the fact that the memory encryption process enforced by TEE (i.e., AMD SEV) did not require much extra memory space.

6 Related Work

**TEE-based Technology.** The capabilities of TEEs have been widely exploited to achieve security, confidentiality and simplicity in many application domains. In the design of secure systems, Baumann et al. proposed the notion of shielded
execution on cloud platforms [6]. Their work addresses the dual challenges of executing unmodified legacy binaries and protecting them from a malicious host. Similar ideas were adopted in data-processing and delegation-based systems to achieve integrity and security without trusting the service providers [32, 37, 47]. Moreover, Tsai et al. demonstrated that a fully-featured library operating system can deploy unmodified applications with the support of a TEE [51]. Shen et al. further introduced secure and efficient multitasking on top of library operating systems with Intel SGX [49]. In the area of blockchain and cryptocurrency, TEEs are often considered a tool to enable trusted and privacy-preserving transactions. Matetic et al. leveraged SGX enclaves to protect privacy of bitcoin light clients [38]. Cheng et al. designed a TEE-based blockchain that executes transactions with confidential input, output and states [15]. Other attempts included building asynchronous access [36], allowing real-time cryptocurrency exchange [7], resource-efficient mining [55] and so on. Moreover, TEEs have also been involved in a diverse collection of optimizations on existing software and hardware, e.g., databases [22, 43, 50, 56], network functionalities [20, 29, 42], storage systems [2, 4, 5, 34]. In addition to applications of TEEs, their design has also been the topic on recent papers proposing improvements interoperability [23, 52], performance [35], and resilience [3, 19].

**Program Analysis.** Program analysis has been a mainstream research direction in the programming language community for decades. Formal verification techniques were proposed to verify high-level programs (usually specified in formal modeling languages) against given specifications of target systems, e.g., safety, liveness, etc. Clarke et al. introduced the technology of model checking to systematically explore the state space of a system and check whether important properties hold or not [15]. Hoare and Roscoe proposed Communicating Sequential Processes (CSP) as a fundamental formalism to model and verify concurrent systems [30, 46]. Alur et al. further introduced timed automata to handle timed systems with properties based on temporal logic [1]. In addition to automatic techniques, theorem proving was designed to deliver rigorous verification with manual or semi-automatic proofs [16, 40]. On the other hand, program analysis has also been applied in practical systems with low-level code, e.g., C++, Java, x86 binary, JVM bytecode, etc. Based on whether the process requires actually executing a program, the analysis is generally categorized into two classes, i.e., static and dynamic analysis. In the context of static program analysis, a variety of researches have been proposed to address fundamental challenges of programs, e.g., understanding semantics [18], memory modeling [25], interprocedural analysis [31, 45], multithreading [21], etc. In contrast, dynamically approaches check programs by instrumenting the code and analyzing it on the fly. Representative types of solutions include fuzzing [12, 26, 44], predictive analysis [8, 9, 24] and symbolic execution [11, 14, 27]. In general, the TCPA framework proposed in this paper is compatible with well-defined types of program analysis and the combination of them as well.

### 7 Conclusion

In this paper, we have highlighted the trusted and confidential program analysis (TCPA) as a trustless technology to achieve agreed regulatory compliance on software among multiple parties without revealing sensitive information about it. We designed the protocol of TCPA for trusted execution environments and developed TCWasm as the very first implementation of TCPA. In our preliminary evaluation with WASM benchmark files, TCWasm demonstrated the potential to handle complicated cases without incurring too much overhead. Further instantiation of TCPA with new types of program analysis and trusted computing solutions is left for future work. We hope that with the rapid development of new TEs, there will be convergence on a security model that serves TCPA well. We have shown that on AMD SEV, it is already a serious proposition.

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