A Secure and Efficient System for Trusted Computing of General Programs in Clouds using Hardware-software Co-design

Qi Hu

23/11/2022

Keywords: Trusted Computing, Binary Rewriting, Distributed System, Software-hardware Co-optimization.

1 Introduction

With the development of cloud computing and big data technologies, more and more applications are being developed for cloud platforms and third-party data centers. However, cloud platform applications often receive various threats, especially the leakage of critical data, which makes many companies reluctant to use the cloud platform. For example, ransomware attacks can steal data. Hackers stole 1 billion records of Chinese citizens from police. Also, Facebook grossly misuses user data for U.S. election. Fortunately, trusted computing prevents confidential violations and protects their applications running on shared servers. In recent years, cloud computing service companies supported confidential computing and provided corresponding Trusted Execution Environment (TEE). For example, Amazon Nitro system [8] uses hardware-based memory isolation to protect data, and Azure [6] provides computing environments for Intel SGX and AMD SEV-SNP and confidential container computing.

However, it is non-trivial to execute general programs, typically legacy (off-the-shelf) applications in a trusted execution environment with security guarantee. The first solution is to **rewrite the source code** and recompile it. Although both SGX and TrustZone provide their SDKs, it requires programmers to divide the trusted and intrusted parts, making it extremely difficult for developers who need to be aware of TEEs. Several automated tools are used to assist in rewriting the source code to make this process easier. For example, Glamdring [20] can automatically split the code into intrusted and trusted parts based on tagged data. Unfortunately, for those programs where the source code is not available, using Glamdring is not feasible. Another solution is to use **shielding** to support general programs. For example, Occlum [38] brings the LibOSes into SGX to support general programs without modification. SCONE [5] provides a secure C standard library interface that allows applications to run in secure containers. They both require an entire program to be run in an enclave. However, shielding supports those programs where the source code is unavailable, putting the entire program into the enclave can increase the size of the Trusted Computing Base (TCB), such as Graphene [10] adding 10

kLoC to TCB. The growth of the TCB size leads to the expansion of the attack surface, which is also an unacceptable solution.

Worse, even when applications can be executed transparently and safely within a TEE, these applications often experience severe performance issues. These problems are usually caused by frequent context switches and memory limitations. Switchless Calls [42] changes synchronous execution to asynchronous execution, which can reduce enclaves switching. VAULT [41] introduces a variable arity unified tree (VAULT), which compresses the Enclave Page Cache (EPC) and saves overhead. Other studies have focused more on reconfigurable trusted hardware, such as TEEOD [29] and BYOTee [4], which use heterogeneous SoC or FPGA to implement some new features. These hardware-related studies are more concerned with new features than performance optimization. CRONUS [16] gives some suggestions on modifying the hardware to speed up trusted computing but does not implement them.

To tackle these ease-of-uses, security and performance issues, this proposal explores algorithms and system designs for executing general programs within TEE securely and efficiently. We will use Programming Language (PL) and software co-design as well as hardware and software co-design to tackle the problem. First, we will explore the algorithms for finding confidential code and sensitive data of general programs (Section 4.1). Then we will use these results to guide our new compiler to make general programs support trusted computing through code rewriting, binary translation or emulation (Section 4.2). By doing so, this approach is general enough to support both general programs running within one process or using a distributed manner (Section 4.3). Finally, we will create performance models for existing TEE hardware (e.g., TEE context switches) to capture performance bottlenecks by inserting statistical code at compile-time, which help the profiler to detect performance bottlenecks at runtime to generate performance-optimized TEE code. By doing so, we will propose new hardware primitives to accommodate the performance model and profiler. And for the performance bottlenecks identified by the profiler, we are ready to perform hardware and software co-optimization to achieve better performance (Section 4.4).

2 Research Objectives

As for my PhD research in trusted computing of general programs, the research objectives are initially expected as follows.

(1) Design a new compiler to support general, especially legacy software on trusted computing systems. This compiler can be implemented in 3 parts, and the overall structure is shown in the Figure 1.

- Dynamic analysis of general software points out which parts of the code are more vulnerable to attack and which data are essential and must be protected.
- Using the analyzed data to guide the in-place binary translation, insert new code segments, which are used to protect code and migrate data into enclaves.

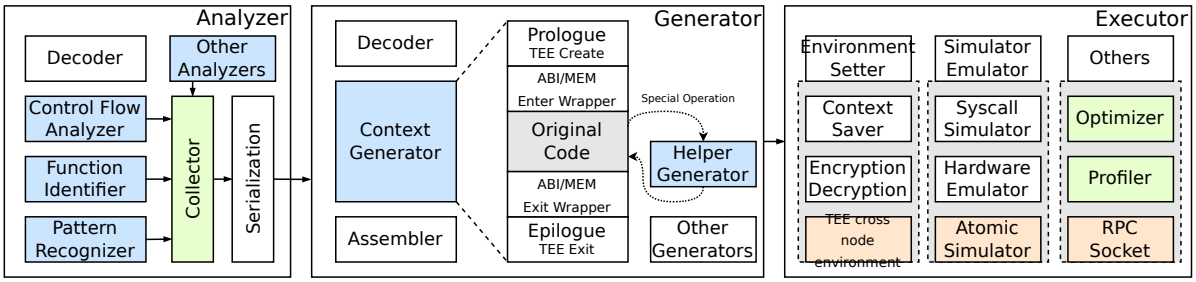

Figure 1: The overall structure of the migration system

- The binary rewriting compiler builds a trusted environment at runtime. Also the migration instruction segments can be generated and added during translation process.

(2) Extend the new compiler to support distributed programs with confidentiality and integrity guarantee.

(3) Create performance models and profilers to analyze performance bottlenecks at runtime, and build new hardware primitives to fit the performance models and profiler. Explore hardware-software co-optimization with the help of the profiler to achieve efficient operation of the entire system.

3 Background of Research

3.1 Trusted Computing and TEE

Various encryption and authentication methods (e.g., TLS and file disk encryption) are often used to prevent confidential data loss, theft or corruption. However, relying on software alone to protect confidential data has many problems, such as software vulnerabilities and reverse engineering cracking [46]. So, it is helpful to use Trusted Execution Environment (TEE) to protect this encryption software and data, which provides an environment shielded from outside interference and the necessary mechanisms to build secure and sensitive applications.

Intel Software Guard Extensions (SGX) is a set of security architecture extensions [24]. It provides the enclave environment that prevents other software from accessing the code and data inside an enclave. Also, when data leaves the enclave and is written into the memory, the data will be automatically encrypted.

ARM TrustZone uses a different approach to TEE by introducing a secure world, which is a new execution environment besides the normal world in the processor [25]. The secure world has multiple privilege levels, just like a virtual machine (VM), which allows an entire trusted software stack to be implemented.

Due to overly complex operations and unacceptable hardware overhead, Intel started to move towards Trust Domain Extensions (TDX) [32, 33], a new trusted computing architecture that introduces a separate trusted hypervisor. The interaction between trusted virtual machines and external intrusted environments should be checked by the security check module Shim.

Since TrustZone lacks confidentiality support, ARM v9 proposes Confidential Compute Architecture (CCA). CCA [3] differs from TrustZone, directly supports in-memory confidentiality capabilities in hardware, and protects users' confidential data.

3.2 Binary rewriting and binary translation

Binary rewriting is a technique for modifying or translating the original binary code without having the source code. According to the characteristics, they can be divided into four categories: static, dynamic, minimal-invasive and full-translation.

Static binary rewriting can use the existing information, such as static data flow analysis and symbol table information, to optimize or enhance existing programs [37, 36]. Dynamic binary rewriting performs alterations during execution, which can be used for performance analysis [22] and hot code patching [9]. Minimal-invasive rewriting is based on branch granularity. It will perform additional instruction at the original location by rewriting into branch instructions. This is often used to add a new function to the original program [12]. Full-translation rewriting can convert binaries at any instruction and usually lift the original binary code into intermediate translation representations. Some open-source tools, like QEMU [7] and Valgrind [27], use full-translation for binary rewriting.

3.3 Distributed system in Trusted computing

With the rise of cloud computing and the increase in data sets in recent years, more and more occasions require the use of distributed systems. While distributed systems, such as Hadoop and Spark, are facing an increasing number of threats.

Distributed MapReduce system VC3 [35] was proposed in 2015, which keeps the code and data confidential, and ensures the correctness and completeness of the results. SGX-PySpark [31] was implemented to protect confidential data with the help of TEE in 2019.

For other systems, such as database, EnclaveDB [30] uses SGX to protect the database engine and ensure high performance. EncDBDB [13] is optimized for column-oriented in-memory databases, also uses SGX for data security.

In recent years, heterogeneous computing systems, such as Computation Storage Architectures (CSA), have also faced data security issues. IronSafe [43] provides a secure processing system for heterogeneous computing storage architectures using a hardware-assisted trusted execution environment.

4 Research Plan and Methodology

4.1 Design a module to analyze general programs

In order to complete the migration of a general programs, particularly legacy system, the first step is to analyze the program and identify the code and data that needs to be migrated. We need to consider three parts: dataflow analysis, recognition algorithm and recognition accuracy.

The first is **dataflow analysis**. The purpose of the analysis is to provide information about the binary program so that the subsequent identification process can proceed smoothly. There are many similar works in the field of binary rewriting to explore the accuracy of binary analysis. BIRD [26] uses a combination of static and dynamic identification methods to improve the accuracy of the analysis. However, some trapped instructions need to be inserted during dynamic disassembly, which is not a good choice for us. Other papers indicate that static disassembly can also achieve good results [2]. So we prepare to implement the static analysis module first and then decide whether to add dynamic analysis based on the accuracy of the analysis.

The next is the **recognition algorithm**. Moat [39] is a detection tool designed by Berkeley that uses automatic theorem proving and information flow analysis methods to discover the possibility of application leakage of secret information in the SGX region by analyzing the assembly language level of the program. Our work can base on Moat, and extract effective identification and verification algorithms from Moat, which can be used in our analysis module.

To evaluate **recognition accuracy**, we will consider it in two parts. *Coverage of analysis*: We will use different test cases to see how well the overall analysis is covered. Since we have access to the source code of these test programs, the coverage of the analysis can be measured by some tools such as Gcov [14] and QEMU [7]. *Correctness of the analysis*: We also use open-source test cases to verify correctness. We would like to compare the results of our analysis tool with the results of the source code after automatic analysis by Glamdring [20] to obtain an accurate analysis.

4.2 Design a new compiler to protect confidential code and data

With the help of an analysis module, it is easy to obtain the code segments that need to be protected and the memory areas where vital data is located.

Code protection. We can use the minimal-invasive translation method for code segments that need to be protected. Similar to the rev.ng [12] and pin [22], we can insert required functions before and after the code segments. We insert the enclave's entry code and enclave's parameters passing code before the segments. Also, enclave's return parameters can be built at the end of the segments. Many more details should be noticed and considered, which need to be discovered and resolved during research.

Data protection. Data protection is more complicated than code protection, especially for global variables. For local variables, we can analyze them, get the program boundary, and put the variables as well as code into enclaves for protection. PtrSplit [21] focuses on identifying C/C++ pointers that prevent the generation of partition boundaries. But for global variables, there is no good solution for now. However, global variables are often not recommended for a highly cohesive and low-coupling system [1, 40], so dropping protection for this part when it cannot be solved is generally not a big deal.

4.3 Extend the binary rewriting compiler into distributed system

Our work will explore two areas related to distributed systems, how to support general distributed programs and enable our system to run on distributed platforms.

Support distributed programs. These distributed programs tend to have more complex features than ordinary programs. For example, OpenMP [11] and MPI+OpenMP [18] will use mechanisms such as semaphores, message communication, etc., which cause problems for both the identification and transformation of our system. We will explore and tackle these challenges during our research process.

Compiler run on distributed systems. How to run our system on a distributed platform is another complex work. DQEMU [45] achieves a distributed dynamic binary translation system. It discusses the implementation issues and performance optimization, including data coherence protocol, locking mechanism, system calls, and remote thread migration. We can take the idea of DQEMU and modify our system to run on a distributed platform.

4.4 Optimize the system by software-hardware co-optimization

Whether running secret code in enclaves or using rewriting compiler for transformation, they both introduce a significant performance overhead. Many studies investigated the overhead of trusted computing and the corresponding optimization method, including avoiding enclave switches [42] and reducing page swaps [28, 41]. But these optimizations may be challenging to implement in our system because it is hard to change the program's original behavior. In addition, binary rewriting also faces significant performance overhead, and existing software optimizations are limited in dealing with these issues [17].

Some studies have proposed several ideas for hardware-assisted acceleration, such as shared memory [16]. So our future work will summarize the existing optimization and search the performance bottlenecks through performance analysis tools, such as Perf, VTune and sgx-perf [44]. After we obtain the bottlenecks of the performance, we can summarize the common characteristics and design or modify some hardware modules to speed up our system and programs, similar to the PIE [34].

5 Expected Outcomes and Significance

To evaluate the effectiveness of our work, as we mentioned in section 4.1, we can use a series of open-source test cases and benchmarks, such as SPEC, UnixBench. We will also consider using SGXGauge [19], a test suite specifically designed to test the performance of trusted systems, to measure the performance of our system. Besides that, we are able to compare our system with other cross-platform TEEs. For example, we can use HyperEnclave [15], TrustVisor [23], Occlum [38] and Graphene [10] as baseline systems for performance analysis.

Although these cross-platform TEEs propose various solutions to the legacy software problem, most research involves modifying libraries and putting them into the enclave. This could lead to the expansion of the Trusted Computing Base (TCB) and the attack surface's expansion.

Our solution uses binary rewriting to place the analyzed confidential code and data into enclaves, hardening the legacy software and reducing the size of TCB. Because of the highly practicality of our new project, we want to open source it and maintain it for a long time. Also, developing the project together with the participation of the open source community, the system can eventually be used as an extension of Huawei's Trusted Intelligent Computing Service (TICS) for commercial implementations, thus making a more significant impact. We anticipate our system for general software can reach the following goals:

(1) The analysis module can efficiently and accurately identify vulnerable code and data. Using analysis module alone can help developers find software weaknesses and flaws.

(2) The binary rewriting compiler can translate legacy software into enclave-protected programs with the help of analysis results.

(3) Our system is extended to support distributed programs.

(4) Based on the performance data, we design or modify the hardware. With hardware-assisted, we expect the performance can exceed other cross-platform TEEs or even approach the performance of native programs.

6 Study Schedule

My PhD research will mainly focus on the study of general software migration in trusted computing systems. To achieve these goals, my preliminary arrangement is as follows.

- 1st Year (2023-2024)
    1. Complete the core courses and choose the elective courses that will help me with my research.
    2. Read the paper and design the whole system, while evaluating and revising our current ideas and plans.
- 2nd Year (2024-2025)
    1. Start to implement our analysis and rewrite system based on first-year design.
    2. Submit the first top paper about our analysis module in OSDI/PLDI/ASPLOS.
- 3rd Year (2025-2026)
    1. Modify and optimize our rewriting compiler.
    2. Extend our system to support distributed programs.
    3. Submit the second paper about our rewriting compiler in OSDI/PLDI/ASPLOS.
- 4th Year (2026-2027)
    1. Review our entire system and analyze their performance bottlenecks.

2. Try to improve the performance of migrated programs by modifying the hardware.
3. Submit the third paper about our work on software-hardware co-optimization in OSDI/PLDI/ASPLOS/MICRO.
4. Complete the PhD graduation thesis.

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