Annotating, Tracking, and Protecting Cryptographic Secrets with CryptoMPK

Xuancheng Jin[1], Xuangan Xiao[1], Songlin Jia[1], Wang Gao[1], Dawu Gu[1], Hang Zhang[2]
Siqi Ma[3], Zhiyun Qian[2], and Juanru Li[1]
[1] Shanghai Jiao Tong University [2] UC Riverside [3] The University of Queensland

***Abstract*—Protecting confidential data against memory disclosure attacks is crucial to many critical applications, especially those involve cryptographic operations. However, it is neither easy to identify involved cryptographic confidential data in a program nor to implement a fine-grained and yet efficient protection. Existing defensive techniques face many shortcomings such as coarse-grained protection or exorbitant overhead. As a result, real world crypto applications seldom applied this kind of protection in practice.**

To make the protection of cryptographic confidential data practical, we design and implement CRYPTOMPK, a source code analysis and transformation system to implement a domain-based memory isolation. CRYPTOMPK first automatically tracks and labels all sensitive memory buffers and operations in source code with a context-sensitive, crypto-aware information flow analysis. Then it partitions the source code into crypto and non-crypto domains with a context-dependent privilege switch instrumentation. By further utilizing Intel Memory Protection Keys (MPK), CRYPTOMPK generates executables with efficient domain switching, protecting them against typical memory disclosure vulnerabilities such as arbitrary memory read. In particular, by using CRYPTOMPK, a large number of intermediate memory buffers that have been previously ignored before are well protected, and thus the security risks are reduced significantly. We leveraged CRYPTOMPK to protect prevalent applications such as Apache and Nginx with widely used crypto libraries (e.g., OpenSSL, LibSodium). CRYPTOMPK only needs several minutes to analyze each of these complex cryptographic programs and incurs at most 9.53% performance overhead for the protected programs.

I. INTRODUCTION

Applications rely on the confidentiality of crypto keys to guarantee the security of executed crypto operations (e.g., HTTPS encryption). Hence, memory disclosure attacks, which could leak the secret crypto key, severely threat the security of those applications. Allowing every instruction of a process to access crypto data is dangerous and unnecessary. In response, various solutions have been proposed in recent years to enhance the protection of crypto-related confidential data in process memory.

A natural strategy is to introduce in-process memory isolation to a program to add special access control for confidential memory buffers. However, doing this correctly and securely can be tricky for crypto software since it is difficult to identify all relevant data that need isolation manually. One of the basic principles of modern cryptography, the Kerckhoffs' Principle [1], states that *everything about the cryptosystem, except the key, is public knowledge*. This principle, however, misleads many memory protection solutions: Most existing approaches only protect the main crypto keys only, which is insufficient to defend against memory disclosure attacks. For instance, some approaches (e.g., Safekeeping [2], Copker [3]) keep crypto keys solely inside CPU, without leaking their plaintext to memory. Unfortunately, most software implementations of modern ciphers (e.g., AES, RSA) generate and store intermediate states of the crypto operations in memory as well, from which the crypto key can be easily derived. Thus the memory disclosure attacks still work even when the proposed defenses are deployed.

Beside the crypto key, a wide variety of runtime data (e.g., the `CryptReleaseContext` of Windows Crypto API) also contain confidential information that needs protection but frequently ignored by most existing defense mechanisms. However, protecting all crypto confidential data in a program is a very sophisticated and challenging task, especially for those real-world complex programs and crypto libraries. It needs to first identify all memory buffers containing confidential data (i.e., *crypto buffers*), and then memory operations allowed to access them (i.e., *crypto operations*). Most protection approaches identify crypto buffers and operations manually (e.g., xMP [4] and libmpk [5]), which is time-consuming and error-prone even for an expert developer. Some other works (e.g., DataShield [6], SeCage [7]) leverage program analysis to automatically locate crypto buffers, however, due to the unawareness of the intrinsic nature of data propagation of crypto operations, they have a severe over-tainting issue (e.g., encrypted ciphertext or decrypted plaintext are also treated as confidential). By allowing more code to access those over-tainted data, attack surfaces to disclose secrets expand significantly. Another problem is how to isolate crypto and non-crypto operations in a process while minimizing the performance overhead. Some defenses (e.g., ConfLLVM [8]) adopt an address-base isolation by inserting checks before every memory access instruction. Although the protection is fine-grained, for most crypto operations that are CPU and memory access intensive, this is obviously inefficient and unacceptable.

Major challenges for generating a crypto secrets protected program include how to track and label all sensitive data and operations in the code automatically, how to grant the permission of an instruction to access sensitive data, and how to implement and deploy a fine-grained yet efficient

Corresponding author: Juanru Li (mail@lijuanru.com) isolation. In this work, we overcome the above challenges by developing a comprehensive in-process isolation solution specifically designed to protect sensitive crypto-related secrets. At a high level, our solution, CRYPTOMPK, relies on a fine-grained and crypto-aware static taint analysis whose results inform a subsequent partition of the program into different protection domains. Specifically, CRYPTOMPK is equipped with three core techniques to address the aforementioned challenges: **1)** CRYPTOMPK automatically determines what data to protect given a small number of initially labelled tags. In particular, CRYPTOMPK avoids the over-tainting issue by conducting a crypto-aware ciphertext/plaintext declassification. **2)** CRYPTOMPK adopts a context-sensitive instrumentation to partition the program in a very precise way. Unlike traditional access control schemes, the attributes of an instruction (e.g., whether it needs to be isolated from a certain piece of sensitive information) can change under different calling contexts according to our analysis results, enabling a more accurate and efficient protection. CRYPTOMPK achieves such a context-sensitivity by generating multiple copies of code instrumented with context-dependent privilege switches. **3)** CRYPTOMPK enforces an efficient domain-based isolation by using the Memory Protection Keys (MPK) hardware feature of latest Intel processors. Furthermore, CRYPTOMPK optimizes the protection granularity to minimize the runtime overhead while maintaining strong security guarantees.

We evaluated CRYPTOMPK on four server programs (Apache, Nginx, OpenSMTPD, vsftpd) with five widely used open source crypto projects (OpenSSL, libsodium, libhydrogen, ccrypt, glibc-crypt) to examine its effectiveness and efficiency against real-world crypto scenarios including file encryption, message protection, SSL/TLS transmission, and password authentication. The results show that CRYPTOMPK can accurately identify both *crypto buffers* and *crypto operations*, and provide reliable protection for both crypto keys and other crypto-related sensitive information without affecting the normal software functionalities, significantly reducing the exposed confidential data. Regarding the performance, it took only several minutes for CRYPTOMPK to analyze large and complex projects offline, and the runtime overhead is at most 9.53% for real-world crypto applications.

In summary, we make the following contributions:

(1) We have designed and implemented the CRYPTOMPK system to automate the tasks of confidential crypto data/code identification (including intermediate data derived from the original) and protected executable generation that incurs negligible overhead at runtime.

(2) We show that secret information leaking through intermediate buffers (derived from the original secret) is very common but often ignored for most crypto applications, leading to broken security guarantees.

(3) We applied CRYPTOMPK to state-of-the-art crypto libraries such as OpenSSL [9] and large server programs such as Apache [10] against any memory disclosure attacks (including the ones that attempt to read the intermediate buffers) to demonstrate the effectiveness of our solution.

(4) We developed an empirical guideline to fully utilize MPK to protect crypto programs in a practical manner. Our solution could be helpful for the protection of other types of sensitive data in computational-intensive code.

Availability. We have open sourced our solution at https://cryptompk.code-analysis.org, where we placed the tool chain, instructions of our experiments, and the tested programs (source code and pre-built binaries).

II. BACKGROUND

A. Problems and Requirements

By transforming memory corruption vulnerabilities into arbitrary memory read primitives, attackers can disclose sensitive data such as crypto keys. In response, many defenses aim to protect credential information in memory. The problem is that for a cryptosystem, if not all sensitive data are protected, the defense would be ineffective. We use an example here to illustrate the difficulties in protecting crypto buffers where secrets are stored in crypto operations. Listing 1 shows the abstracted AES encryption in ccrypt [11], a cryptographer developed data encryption tool: In this example, the `encrypt` function generates an AES key from a secret `passwd`. The key generation procedure propagates the secret information of `passwd` to several intermediate buffers such as the `rkk` buffer and the `keyblock` buffer. Consider the situation that an attacker leverages an arbitrary memory read vulnerability to scan the memory, not only the `passwd` buffer but all those intermediate buffers that store crypto secrets should be protected. Otherwise, attacker could still exploit the leaked intermediate buffers to recover secret keys.

```
void encrypt(void *ciphertext, void *plaintext,
             char *passwd) {
    roundkey rkk;
    hashstring(passwd, keyblock);
    xrijndaelKeySched(keyblock, 256, 256, rkk);
    xrijndaelEncrypt(ciphertext, plaintext, rkk);
}
```

🟩 Secret 🟨 Non-secret

Listing 1: An example of secret propagation in ccrypt

Unfortunately, existing works often fail to comprehensively protect crypto sensitive information. Many protection approaches intuitively focus on an original secret but ignore its propagation. Take the case of using libmpk [5] to protect OpenSSL against the infamous HeartBleed vulnerability [12] as an example. The protection only defended SSL/TLS private keys from potential information leakage by storing the keys in isolated memory pages. In particular, they only protected data types that store private keys (e.g., `EVP_PKEY`) with an isolated memory region, but do not consider the secret propagation and let secret information leak to intermediate buffers. Although they additionally protected functions that need to access the private key, we will demonstrate in Section V-E that if only the private key is protected, an attacker could exploit HeartBleed vulnerability to retrieve other intermediate states and still recover the secret key.

B. Challenges

In short, the major research challenge of this paper is to determine the minimum part of code that we must grant crypto buffer access privilege, and block any other accesses (e.g., a buffer overread somewhere in the application process). To accurately label all crypto buffers in a process, and implement a fine-grained in-process isolation to restrict irrelevant code from accessing secret information. Existing works face the following challenges:

How to accurately label crypto memory buffers and related operations? Crypto data are widely distributed at different regions of process memory (e.g., stack, heap, global variable). Existing solutions (e.g., DataShield [6], MemSentry [13], libmpk [5] and xMP [4]) provide primitives to isolate sensitive information in specific memory regions. Nonetheless, they do not answer the question of how to find all those crypto memory buffers automatically. A straightforward idea (e.g., the solution adopted by SeCage [7]) to find all crypto buffers is to track the propagation of initial secret with taint analysis, and restrict the access against all reference data. This strategy, unfortunately, suffers from over-protection issue because it propagates taint tag to plaintext/ciphertext. In the example of Listing 1, if we define the `passwd` as the taint source, a standard taint analysis would also taint the `ciphertext` at Line 6. In this situation, the tainting of ciphertext buffer (and its following propagation) will significantly enlarge the protection scope.

How to isolate crypto data from unauthorized memory accesses appropriately? The isolating of crypto data inherently incurs performance overhead. A very fine-grained isolation may introduce unacceptable overhead, especially for CPU-intensive and time-sensitive crypto operations. On the other hand, a less fine-grained isolation may leave an attack more opportunities in stealing sensitive data. Therefore, it is important to choose an appropriate protection granularity to balance security and performance overhead.

How to implement the isolation without changing the execution model? Some in-process isolation approaches require to modify the execution model of the program (e.g., moving part of the program to TEE or SGX). This involves heavy modification of existing code and often introduces compatibility issue, thus is often infeasible in most cases.

C. Solutions

Analysis-driven Sensitive Data Labeling (Section III-C). Instead of asking developers to manually label crypto memory buffers and related operations, we make use of a static code analysis to help label those information automatically. Particularly, the adopted static code analysis employs a special crypto-aware, context-sensitive information flow propagation strategy to label crypto memory buffers effectively.

Hardware-supported Domain Isolation (Section III-D).

To protect labeled sensitive data, we associate them with a *crypto domain*, and fulfill a domain based isolation, which adds an access permission to qualify the access of crypto secret. When the execution shifts between crypto and non-crypto domains, instead of using software based heavyweight access permission granting mechanisms (e.g., hypervisor based), we utilize Intel Memory Protection Keys (MPK) technology [14] to implement a processor-featured privilege switching. This guarantees an efficient protection against crypto applications.

Compiler-assisted Code Transformation (Section III-E). Instead of partitioning the program into different modules to implement isolation, we leverage the LLVM infrastructure to conduct an IR level code transformation (i.e., inserting privilege switching instructions, re-allocating memory buffers, adjusting call graph, etc.) while keeping the original execution model. Without porting the entire crypto application or any part of it to a secure world (e.g., SGX or Trustzone), a protected executable still runs in the same environment without special deployment.

III. CryptoMPK

A. Threat Model and Concepts

In this paper we assume attackers are able to launch memory disclosure attacks due to memory safety issues. The goal of an attacker is to disclose crypto secrets (e.g., AES key, RSA private key) from the memory of a process. We only focus on memory disclosures caused by vulnerabilities such as HeartBleed [15] and do not consider attacks that compromise the integrity of execution (e.g., a control flow hijacking caused by an arbitrary memory write). We do consider the solutions that protect the integrity of a program [16], [17], [18] can be complementary to ours. In fact, as we show later in §V-D, we have partially integrated with one such solution successfully. Nevertheless, ensuring perfect integrity is still an unsolved problem which we currently consider to be out-of-scope.

We assume code vulnerabilities exist in an application, and attackers could remotely exploit such vulnerabilities to access sensitive data (e.g., crypto keys) in process memory of the vulnerable application. We do not limit the type of memory disclosures, which could either be an out-of-bound read or an arbitrary address read. Nevertheless, this paper only focuses on memory safety issues and does not consider information leakage related side-channel attacks, both physical (e.g., cold boot attack [19]) and logical (e.g., Meltdown [20] and Spectre [21]) ones.

We use the concepts of *crypto buffer* and *crypto operation* to help analyze the program. We define them as follows:

***Definition** 1:* A *crypto buffer* is defined as a continuous memory region (stack, heap, or global) that stores crypto secrets including master keys and intermediate results of cipher executions. Note that a buffer stores plaintext or ciphertext is not considered as a crypto buffer because it does not need to be protected.

***Definition** 2:* A *crypto operation* is a memory operation (either read or write) that access a crypto buffer. We consider crypto operation to be security-sensitive if it accesses crypto buffer, and thus should be protected to guarantee the confiden-

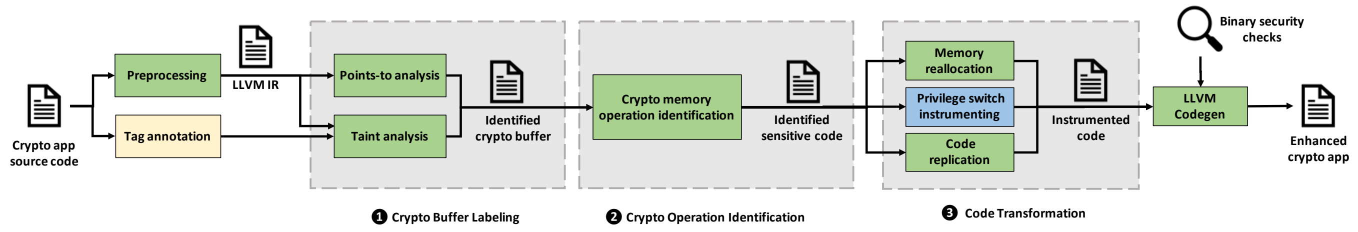


Fig. 1: An overview of CryptoMPK workflow

tiality. For example, a memory read instruction that accesses round key of AES encryption is defined as a crypto operation.

B. Overview of CryptoMPK

Our solution, CryptoMPK, is a source code analysis and transformation system that adds fine-grained, context-sensitive in-process isolation for credential data in crypto applications. At a high level, CryptoMPK labels crypto buffers and crypto operations in a program automatically, and isolates crypto and non-crypto operations to reduce the unnecessary accesses of credential data. As Figure 1 depicts, CryptoMPK adopts a workflow consisting of a pre-analysis phase and three major phases. In its pre-analysis phase, CryptoMPK compiles program source code to LLVM Intermediate representation (IR) for the following analyses, and a manual annotation on source code is required to help CryptoMPK understand specific crypto attributes of the analyzed target. After the pre-analysis phase, CryptoMPK first conducts a **crypto buffer labeling**, which relies on static points-to analysis and taint analysis to label crypto buffers. Next, CryptoMPK employs a **crypto operation identification** to locate memory accesses and management operations on crypto buffers. After that, CryptoMPK leverages the results of previous analyses to fulfill a **code transformation**. The transformation relocates labeled crypto buffers into a protected memory region, replicates functions to be protected for different contexts, and partitions the program into a *crypto domain* and a *non-crypto domain*, instrumenting privilege switches on crossing boundaries. Finally, CryptoMPK generates crypto domain isolated binary code, and utilizes supplementary security checks to inspect and eliminate potential bugs (e.g., using binary code rewriting to remove ROP gadgets from the executable).

To identify crypto buffers and operations, CryptoMPK traverses source code of an analyzed program and handles each instruction using a **crypto-aware and context-sensitive taint propagation**. The crypto-aware feature proves that CryptoMPK would not over-label buffers such as ciphertext, and the context-sensitive feature guarantees a context-dependent domain isolation. Based on the identification results, CryptoMPK modifies LLVM compiler to generate programs with customized memory management and in-process privilege switching, which implement a **crypto domain based isolation**. Only instructions in the crypto domain are allowed to access crypto buffers, and any sensitive data access from non-crypto domain will trigger a segmentation fault, which defends against unauthorized memory accesses such as memory disclosure attacks.

C. Automated Crypto Buffer Labeling

CryptoMPK employs an automated crypto buffer labeling to replace the traditional time-consuming and error-prone manual annotation. It only requires developers to manually annotate which buffer stores the *initial secrets*, and then uses the initially annotated secret data as its taint source. For instance, the encryption key and the private key are initial secrets for symmetric-key ciphers and asymmetric-key ciphers, respectively. With the annotated initial secrets as taint sources (with a `crypto` taint tag), CryptoMPK propagates taint tag to label crypto buffers. It starts with the direct usages of initial secrets, and traverses the IR instructions as abstractly interpreting the code. It also leverages a points-to analysis to accompany the taint analysis, determining the target of pointers, improving the accuracy of both control-flow and data-flow construction. After the traversal, CryptoMPK generates an abstract representation for each variable, which contains taint tags and points-to information.

Unlike normal taint analysis, the taint propagation of CryptoMPK is crypto-aware. It considers the declassification of plaintext/ciphertext. That is, unlike common taint analysis that propagates the `crypto` tag to the output ciphertext or plaintext (and thus leads to an over-tainting from the perspective of cryptography), our crypto-aware taint analysis adds the tag of crypto key to neither plaintext nor ciphertext. To handle this case, our analysis requires an extra manual annotation against plaintext and ciphertext buffers. Then, in the crypto-aware taint propagation, CryptoMPK assigns those annotated buffers with a special `mutually-exclusive (mxor)` tag. When the cipher mixes crypto keys with either plaintext or ciphertext, the `mxor` tag will "eliminate" the `crypto` tag. This helps CryptoMPK fulfil the declassification of plaintext/ciphertext without specifically defining their propagation rules.

Moreover, CryptoMPK uses context-sensitive analysis to attribute different tags for a same memory buffer under multiple contexts. Taking Listing 2 as an example, the `xreadline` function (Line 1-8) is used to read a text line from a file, and allocate a buffer to store the read content. In this example, the property of memory buffer allocated by `xreadline` (Line 2) depends on the invoking context. If `xreadline` is invoked by the `readkey` function (Line 12), the allocated memory buffer should be labeled. In other cases (e.g., invoked by the `prompt` function at Line 19) the allocated buffer is not sensitive. In response, CryptoMPK generates multiple contexts for each function according to the execution. In each context, the abstract representation of involved variables are independent.

Hence CryptoMPK could assigns more than one property for a variable. With such a context-sensitive analysis, CryptoMPK executes a fine-grained isolation in the following code transformation phase (detailed in Section III-E2).

D. Crypto Operation Identification

After labeling crypto buffers, in its second phase, CryptoMPK identifies which parts of the program are allowed to access those crypto buffers. At the IR level, CryptoMPK defines crypto operations as instructions that access memory of crypto buffers. Since the first phase analysis has already obtained the abstract representation of each variable, in a second traversal against the IR, CryptoMPK leverages the obtained information to identify crypto operations. In particular, CryptoMPK identifies two types of crypto operations.

1) **Memory Access**: In LLVM IR, `load` and `store` are used to access memory. By checking the accessed address arguments (as crypto or non-crypto buffer) of these instructions, CryptoMPK determines which instructions access crypto buffers, and attributes them as crypto operations.
2) **Memory Management**: To further manage crypto buffers, CryptoMPK introduces its customized memory management to replace the existing ones in a program. Thus it also needs to identify memory allocation and de-allocation operations. CryptoMPK considers a memory allocation operation as sensitive if it allocates a crypto buffer, and a memory de-allocation operation as sensitive if its pointer argument points to a crypto buffer.

E. Code Transformation

With the labeled crypto buffers and the identified crypto operations, CryptoMPK performs a code transformation at LLVM IR instruction level to partition the program into a crypto and a non-crypto domain. It first relocates crypto buffers to a protected memory region, and then inserts privilege switches between crypto and non-crypto domains.

1) Memory Relocation: CryptoMPK relocates different kinds of crypto buffers into a protected memory region in a unified way. In detail, CryptoMPK replaces both stack and heap allocations with functions of a customized memory manager (see details in Section IV-F), Next, CryptoMPK replaces the corresponding de-allocation functions for on-heap buffers with the customized one for protected buffers, and inserts extra de-allocation operations in function epilogues to explicitly release protected buffers that are originally on stack. For global crypto buffers, CryptoMPK re-allocates them during the initialization of the program and de-allocates them at the program termination.

Since the labeling of crypto buffer is context-sensitive, CryptoMPK correspondingly executes a context-dependent memory allocation. In Listing 2, for example, the `xreadline` function allocates `buf` for data read from external files. However, for different contexts, the allocated memory buffer could be either a crypto buffer or a non-crypto one. In this example, only the allocated buffer under the context of `readkey` (Line 12) is labeled as crypto buffer. Thus CryptoMPK does not directly replace `malloc` in Line 2. Instead, it replicates the `xreadline` function (one for crypto buffer allocation, and the other for non-crypto buffer allocation) to implement a fine-grained management (see Section IV-F).

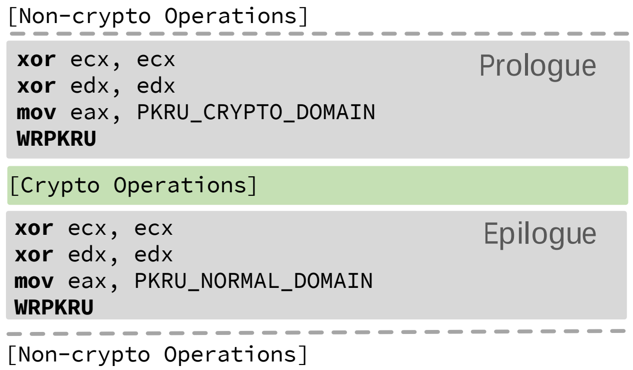
```
1   char *xreadline(int fd) {
2     char *buf = malloc(MAX_LEN);
3     for (int i = 0; i < MAX_LEN; i++) {
4       int n = read(fd, buf+i, 1);
5       if (n <= 0 || buf[i] == '\n') return buf;
6     }
7     return buf;
8   }
9   - - - - - - - - - - - - - - - - - - - - - - -
10  char *readkey() {
11    [...]
12    char *line = xreadline(fd);
13    [...]
14    return line;
15  }                                  Sensitive context
16
17  char *prompt() {
18    [...]
19    char *line = xreadline(fd);
20    [...]
21    return line;                     Non-sensitive context
22  }
```

Listing 2: An example of context-dependent memory allocation

Instead of invoking time-consuming system calls (e.g., `mprotect`) to implement a memory page level access control, CryptoMPK leverages the Intel MPK instructions (e.g., `WRPKRU`) to fulfill an efficient privilege switch. MPK features a protection key (`PKEY`, stored in the 32-bit `PKRU` register) to control the access permission of a memory page. By binding a `PKEY` to a group of memory pages, access permission of those pages can be set simultaneously. CryptoMPK first relocates those labeled crypto buffers to a memory region maintained by its own memory manager, and then binds memory pages in this protected region with a `PKEY`.

2) Privilege Switch Instrumenting: To grant or revoke access permission against protected buffers at runtime, CryptoMPK instruments privilege switches between crypto domain and non-crypto domain. User process executes a `WRPKRU` instruction to updates the `PKRU` register. CryptoMPK thus adds *crypto domain prologue* and *crypto domain epilogue* to the binary code to fulfill MPK privilege switching as Listing 2 illustrates. Only after an execution of crypto domain prologue, the later crypto operations are allowed to access protected memory buffers, and after an execution of crypto domain epilogue, protected memory buffers restore to an inaccessible state for non-crypto operations.

For current MPK-enabled processors, up to 16 PKEYs can be used simultaneously. This allows CryptoMPK to support more than one crypto domain with multiple crypto keys. In this paper, we only considered the protection with one crypto domain. Also note that the privilege switch mechanism is independent to other parts of CryptoMPK. Hence, it could be easily extended to adapt different scenarios. For instance, in July 2020, Intel have proposed a new PKS [22] feature to support kernel level memory page access control. Since PKS is



```
[Non-crypto Operations]
xor ecx, ecx
xor edx, edx
mov eax, PKRU_CRYPTO_DOMAIN
WRPKRU
[Crypto Operations]
xor ecx, ecx
xor edx, edx
mov eax, PKRU_NORMAL_DOMAIN
WRPKRU
[Non-crypto Operations]
```

Fig. 2: MPK privilege switching at binary code level

the kernel-version of MPK, CRYPTOMPK could be extended to protect crypto secrets in kernel easily. Similarly, CRYPTOMPK could leverage the shred isolation primitives [23] to protect ARM executables.

3) Code Replication: CRYPTOMPK generates different versions of code for different contexts. Algorithm 1 illustrates how CRYPTOMPK creates multiple versions of code (functions) for different contexts. For instance, to protect the `xreadline` function in Listing 2, CRYPTOMPK creates a protected version `xreadline_r1` and replaces the invoking at Line 12, and a non-protected version `xreadline_r2` for the invoking in the `prompt` function. Since Line 4 and 5 have been labeled as crypto operations, in `xreadline_r1`, CRYPTOMPK inserts privilege switches before and after them*. Moreover, by replacing `malloc` in Line 2 with a customized memory allocation function, CRYPTOMPK reallocates `buf` to the protected memory region in `xreadline_r1`.

One problem of naive code replication is that it may lead to a significant code size bloating. As shown in Figure 3a, `xreadline` in context of `main` and `readkey` is same in transformation since their semantics in two contexts is identical. Thus generating two versions of these contexts are unnecessary. CRYPTOMPK further introduces a function deduplication algorithm to avoid generating redundant code (Algorithm 1). It works by calculating a signature for the transformation scheme of each context. Contexts of the same function with the same signature are considered identical and will share a single piece of code. In this way, code size bloating introduced by function replication is minimized.

The signature of a context is calculated as follows:

1) **Collecting the information of the instructions operating on crypto buffers.** Actual transformations will be done around these instructions (as defined in §III-D). For each of them, CRYPTOMPK records its unique identifier (e.g. address) and its type (e.g. Load).
2) **Collecting the signatures of sub-contexts.** Two contexts can share the same code only if their callees are also the same. Thus for each CallInst, CRYPTOMPK records its identifier and type as that in Step 1, plus the name and signature of the called sub-context.
3) **Generating the final signature.** Information from previous steps fully describes the transformation scheme of the context, thus CRYPTOMPK uses `hash_combine()` in boost [24] to calculate its hash as the final signature.

```
Data: Context set $C$ in post-traversal order
Result: Output function set $F$
begin
    $F \leftarrow \{\}$
    forall c ∈ C do
        if $c$ is root context then
            $c.f' \leftarrow c.f$
        else
            $S_f \leftarrow$ getFunctionVariants $(c.f)$
            $s_c \leftarrow$ signature $(c)$
            if $s_c \notin S_f$ then
                $c.f' \leftarrow$ copyFunction $(c.f)$
                $S_f \leftarrow S_f \cup \{s_c\}$
            else
                $c.f' \leftarrow$ variant in $S_f$ with signature $s_c$
            end
        end
        forall $I' \in c.f'$ do
            if $I'$ is a call by function pointer then
                replace $I'$ with direct function calls
            end
        end
        forall $I' \in c.f'$ do
            if $I'$ is a call instruction then
                $I \leftarrow$ mapped instruction for $I'$ in $c.f$
                $c' \leftarrow$ subcontext called by $I$ in $c$
                $I'.calltarget \leftarrow c'.f'$
            end
        end
        $F \leftarrow F \cup \{c.f'\}$
    end
    return F
end
```

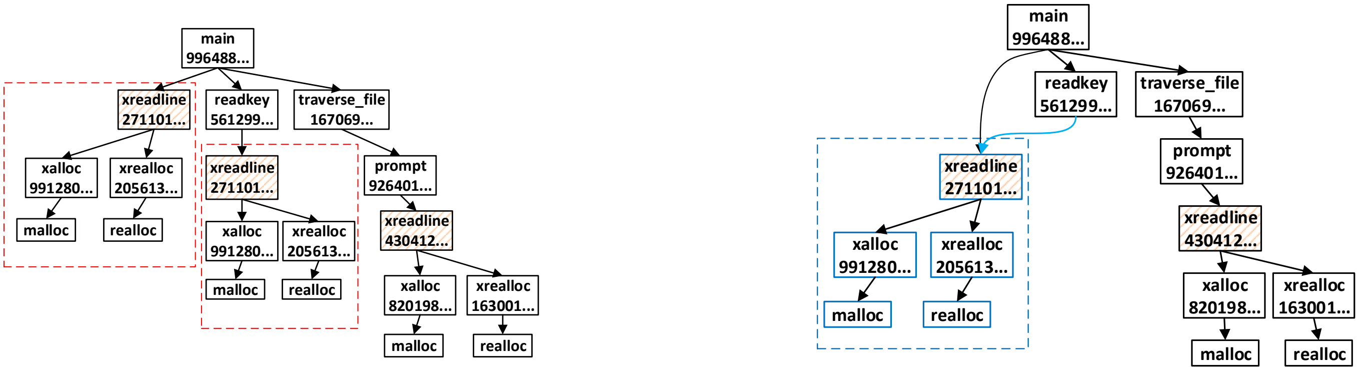
Algorithm 1: Function Replication

IV. IMPLEMENTATION

A. Static Program Analysis

Static analysis is suitable for checking confidential data leaks [25]. CRYPTOMPK relies on a context-sensitive points-to analysis to identify crypto buffers and operations. Since CRYPTOMPK aims to protect crypto operations comprehensively, it seeks to both accurately identify all secrets while only allowing relevant code to access them. Nevertheless, static points-to analysis is undecidable for C programs [26] and thus fundamentally imprecise [27], [28]. Consequently, CRYPTOMPK modified the design of Dr. Checker [29] to implement a sounder analysis. The following design changes were made for the goal: 1) CRYPTOMPK does not rely on depth-based heuristics or strong-update features to speed up the analysis, but keeps all points-to information; 2) CRYPTOMPK adopts a more sophisticated design of *alias objects* to support points-to tracking in nested structures, global variables, and casted pointers, which are common in crypto applications but are oversimplified in Dr. Checker; 3) for dangling pointers with

*Inserting privilege switches in a loop may lead to performance issues. We will discuss optimization strategies in Section IV-D



(a) Original call graph. Three versions of `xreadline` are separately invoked by three functions (`main`, `readkey`, `prompt`). However, the context signatures of `xreadline` invoked by `main` and `readkey` are identical.

(b) Call graph after applying function de-duplication. CryptoMPK only maintains one copy of `xreadline` for two identical context signatures (271101).

Fig. 3: Call graphs before and after function de-duplication

which no object is found associated, CryptoMPK would fill in hollow objects to track their propagation thereafter.

To further ensure efficiency when analyzing complex crypto code bases, CryptoMPK employs two major strategies to counter the common challenges in a context-aware analysis. To address context explosion, it prunes off certain contexts where the corresponding functions are marked as orthogonal to the sensitive dataflow. To address points-to explosion, we made our observation that most of the objects are associated with memory pools (e.g. `BN_POOL` in OpenSSL [9]), and that they cannot be distinguished without proper abstraction [30]. Thus, CryptoMPK represents the pool with a single object without compromising the precision. On its finish, the static program analysis produces a tree of context objects, representing the call tree of the analyzed program. Each context object contains information on the taints and points-to relations among local values and allocated memory objects.

B. Labeling Crypto Buffers

We envision two types of users of CryptoMPK: (1) crypto library developers (the primary type) who are familiar with the logic of the various crypto functions and any sensitive data generated within the library, e.g., a private key. (2) application developers who use crypto libraries and are at least familiar with the APIs exposed by crypto libraries. This is important because sometimes crypto secrets can be generated by applications (host programs), e.g., supplying a password to a crypto hash function. Therefore, we currently also require application developers to label such secrets in order for CryptoMPK to track their propagation in the application context as well as the crypto library context. Later in §V-B and §V-C, we will report cases where applications-generated secrets do propagate in the application context (although not very often) and need to be protected. In both cases, CryptoMPK asks developers to annotate only the initial tags in the source code, which is shown to be small in both prior work [23] and our evaluation in §V-B. The propagation of tags is performed completely automatically by CryptoMPK during static analysis.

To annotate the initial tags, developers need to determine the crypto functions (either provided by the crypto library or directly implemented as a part of the host program), and identify the semantics of their input parameters to find key and plaintext/ciphertext. Next, developers could choose to directly annotate the key with a `crypto` tag and the plaintext/ciphertext with a `mxor` tag, or shift the annotation (and thus the protection) to earlier stage program inputs. For example, in Listing 1 developers could either label the `rkk` parameter of the `xrijndaelEncrypt` function with a `crypto` tag, or instead label the user input `passwd` string, which helps generate the AES key. In the future, we plan to automate this process by having crypto library developers annotate the outer most tags (e.g., parameters of a crypto API) and backtrack to the origin of such variables (possibly defined in the application context). That way, we can shift the burden of annotation to only the crypto library developers.

```
1 void do_encrypt() {
2   #pragma tainter cryptotag(passwd)
3   __cryptotag_fdf0f8a65855a52b(passwd);
4   #pragma tainter mxortag(plaintext)
5   __mxortag_fdf0f8a65855a52b(plaintext);
6   encrypt(ciphertext, plaintext, passwd);
7 }
```

Listing 3: An example of initial tag annotating

CryptoMPK implements a compiler directive in clang front-end to help annotate the code. Listing 3 gives an example of the initial annotating: the developer is required to explicitly add a `#pragma` annotation (Line 2) to annotate the initial secret (`passwd`). With this information, CryptoMPK implicitly inserts a function (Line 3) to help set the taint source (with a `crypto` tag). Then our analysis-driven labeling automatically propagates the initial `crypto` tag. Moreover, the developer also needs to annotate an initial `mxor` tag (Line 4) to indicate that the `plaintext` buffer carries a `mxor` tag).

For those functions without IR code to analyze, CryptoMPK implements pre-defined rules in taint and points-to propagation. For instance, CryptoMPK handles a `memcpy` invoking by checking the taint tag of source object and the destination object. Modern Processors also adopt extend instruction set (e.g., AES-NI) to execute crypto algorithms, and many crypto libraries have already integrated cipher implementations specifically optimized for those instruction set extensions. We observed that at LLVM IR level, such an instruction (e.g., an AES-NI instruction) is implemented as an LLVM intrinsic function invoking. Therefore, CRYPTOMPK also handles such instructions as external functions with pre-defined rules.

C. Identifying Crypto Operations

After the crypto buffer labeling, CRYPTOMPK conducts a second code traversal to identify crypto operations. For each memory-related operation, if any of its operands is associated with a `crypto` tag, it is considered as a crypto operation.

External functions with pointer arguments, due to the lack of source code to analyze or modify, are also considered as memory operations. Ideally, we could conduct binary code analysis to analyze an external function/library and utilize a binary code rewriting to generate a protected version. We leave this as a future work of this research, and currently adopted a runtime permission granting mechanism for external functions (see Section IV-G).

D. Privilege Switch Instrumenting

Ideally, CRYPTOMPK inserts privilege switches right before and after a series of continuous crypto operation instructions to minimize the attack window. However, if we insert too many privilege switches, especially in hotspots, the execution will often suffer from performance issue (our micro-benchmark shows that the `WRPKRU` instruction takes about 20 to 30 CPU cycles, a lot more than an ordinary arithmetic instruction). To address, CRYPTOMPK trades off performance by protecting different instrumentation granularity against the code. For performance critical applications, CRYPTOMPK applies a function level crypto domain isolation for those **hotspot functions**. CRYPTOMPK considers the entire hotspot function as sensitive, and inserts privilege switches before and after any instructions that invoke it.

Hotspot functions are identified using a heuristic method. In general, CRYPTOMPK calculates a Q score for each context (Eq. 4), estimating the ratio of crypto operations within all memory operations. To resemble the case in real execution, instructions in loops are additionally weighted (Eq. 2), and numbers of instructions in sub-contexts are also estimated (Eq. 3). If the final Q_{ctx} is higher than a pre-defined threshold (0.25 here), CRYPTOMPK considers the function represented by ctx as a hotspot function. For recursive functions, due to their limited usage in crypto programs and the great analysis difficulty, CRYPTOMPK conservatively protects the entire recursive invocation.

$$T_{inst} = \begin{cases} 1 & inst \text{ is a crypto operation} \\ Q_{ctx'} & inst \text{ is a callinst, } ctx' \text{ is its target} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$L_{inst} = \begin{cases} 10 & inst \text{ is in a loop} \\ 1 & inst \text{ is not in a loop} \end{cases} \tag{2}$$

$$S_{inst} = \begin{cases} L_{inst} * 30 & inst \text{ is a callinst} \\ L_{inst} & inst \text{ is a memory operation} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$Q_{ctx} = \frac{\sum S_{inst} * T_{inst}}{\sum S_{inst}} \tag{4}$$

E. Invocation with Function Pointer

After CRYPTOMPK replicates a function, the next step is to replace all related invocations to guarantee the correctness of control flow. However, for a function invocation using function pointer, the control flow is often determined dynamically and we cannot directly rewrite the invocation. CRYPTOMPK therefore refers to a function pointer expanding technique used by Glamdring [31]. In our implementation, CRYPTOMPK first determines all possible candidates of a function pointer based on the results of points-to analysis, then replaces the function pointer invocation with expanded direct calls. In the example of Listing 4, CRYPTOMPK first evaluates the original invocation with `funcptr`, finding two possible invoking targets (`func1` and `func2`). Then CRYPTOMPK adds two conditional invocations to the two replicated versions (`func_r1` and `func_r2`). For unexpected targets, they are invoked in a fallback branch without replication.

```
- funcptr(/*args*/);

+ if (funcptr == func1)
+   func1_r1(/*args*/);
+ else if (funcptr == func2)
+   func2_r2(/*args*/);
+ else
+   funcptr(/*args*/);
```

Listing 4: Function pointer expanding

F. Crypto Buffer Management

To manage sensitive data in a unified way, CRYPTOMPK allocates all crypto buffers on a secure heap. It customizes the Jemalloc [32] allocator to support secure memory management. In detail, the customized allocator (namely `m_malloc`) binds the allocated memory pages to a specific PKEY. Hence the access control of crypto buffers can be fulfilled efficiently by updating the PKRU register. In addition, it maintains a global table to record the pointer addresses of all crypto buffers, and replaces all memory de-allocation operations (including vanilla `free`) with the unified `m_free` function. When freeing a buffer using `m_free`, it checks the global table to choose the underlying de-allocator to use, either the customized version corresponding to `m_malloc` for crypto buffers, or the standard `free` for non-protected buffers.

Allocating all sensitive crypto buffers on our secure heap may introduce runtime overhead especially for stack memory operations. An optimization strategy adopted by CRYPTOMPK is that, if the length of a buffer is no more than a primitive scalar type (i.e. 8 bytes), CRYPTOMPK will not modify its stack memory allocation. Instead, CRYPTOMPK inserts memory zeroing code in function epilogue to clean those small buffers immediately after the function execution. We argue that this kind of buffers seldom store long-term secret and a memory sanitization rather than secure isolation is able to defend against memory leak.

G. Runtime Checks

The static code analysis of CRYPTOMPK may not perfectly identify all crypto operations due to the imprecision of points-to analysis. If a privileged operation is not correctly identified, a runtime exception will be triggered and the protected program will crash. To further prove the robustness, CRYPTOMPK does not solely rely on static analysis but leverages a dynamic analysis to help find those operations. We argue that developers often possess enough test cases to execute the program. With these test cases, CRYPTOMPK conducts an extra runtime test to check the protected program and finds potential exceptions.

In detail, CRYPTOMPK links the protected program with a shared library that captures all runtime segment faults caused by MPK privilege violation. When the linked shared library captures a `PKEY` related segment fault during the test, it records the address of the fault instruction and the accessed memory buffer, and then temporarily enables access privilege for this instruction to continue the execution. After the entire execution, all unauthorized memory accesses are sent to developers for a manual verification. If the manual analysis confirms a memory access is actually legal (which implies that the accessed memory buffer should be labeled as crypto buffer but is missed by our static analysis), CRYPTOMPK will automatically add a `crypto` tag for the related buffer and runs the static analysis again to identify more crypto operations.

In addition, if an unauthorized memory access occurs in an external library function (without source code and thus CRYPTOMPK cannot rewrite it), CRYPTOMPK links a specific segment fault handler to handle the exception, which restricts the range of code to access sensitive crypto buffers but suffers from performance slowdown.

V. EVALUATION

A. Experiment Setup

We use two sets of widely used open source projects to evaluate CRYPTOMPK. The first set contains four popular crypto libraries including the famous OpenSSL [9] library, the libcrypt of GNU libc [33], and two modern crypto libraries, libsodium [34] and libhydrogen [35], which aim to provide easy-to-use, hard-to-misuse functionalities. The second set contains four widely used Linux web server programs (Nginx [36] and Apache [10] as HTTP servers, vsftpd [37] as FTP server, and OpenSMTPD [38] as SMTP server), and ccrypt [11], a cryptographer developed cross-platform data encryption utility. Details of the tested libraries and programs are shown in Table IV in Appendix.

We ran our experiments on a server running Ubuntu 18.04 x64 with two Intel Xeon Gold 5122 Processors (each has eight logical cores at 3.60 GHz) and 128GB RAM. The current implementation of CRYPTOMPK runs on top of LLVM 10.0.1. In our experiment, we first utilized CRYPTOMPK to analyze all programs, then we execute the analyzed programs with runtime checks instrumented, finally we generated executables to evaluate the performance overhead [†]. In the following, we report our experimental results.

B. Annotated Tags and Costs

We tested CRYPTOMPK by considering four typical application scenarios and the tested cases are detailed in Appendix. For all test cases, we evaluate the number of manually annotated tags and the approximate amount of effort expended for each program.

For Apache/Nginx+OpenSSL, we only need to annotated **seven** initial `crypto` tags in OpenSSL including six variables of the `pkey` struct that stores private key, and the `AES_KEY` key buffer of `AES128-GCM` API. We additionally annotated **two** initial `mxor` tags to plaintext buffer of `RSA-sign` and ciphertext buffer of `RSA-verify`, and plaintext/ciphertext buffers for `AES128-GCM` encryption/decryption, respectively.

For the message protection cases, we annotated **three** initial `crypto` tags to those crypto key parameters of both the used sign/verify APIs (e.g., `hydro_sign_{create, verify}` of libhydrogen) and the used encrypt/decrypt APIs (e.g., `crypto_secretstream_xchacha20poly1305_-keygen` of libsodium, `hydro_secretbox_encrypt` of libhydrogen). After that, we annotated **four** initial `mxor` tags to plaintext/ciphertext parameters of those APIs.

Instead of annotating parameters of crypto functions, in the case of ccrypt encryption, we annotated **four** initial `crypto` tags to the buffer allocated by the `readkey` function in host program. This helps CRYPTOMPK protect crypto secrets in the entire program. And we annotated **three** `mxor` tags to plaintext buffers, which are read from the input data file.

OpenSMTPD and vsftpd leverage the `crypt` password hashing function to transform user-provided passwords into a hash value. We observed the user-provided passwords are not only used by the `crypt` function but also other part of the host program, and thus we annotated the initial `crypto` tag to `passwd` buffers in host programs, and annotated the `mxor` tag to the `salt` parameters of the `crypt` API. An additional case is that for vsftpd with a parent thread and a child thread, we annotated **two** extra initial `crypto` tags separately to `p_sess->ftp_arg_str` of `handle_pass_command` in its parent thread, and `password_str` of `process_login_req` in the child thread. Therefore, CRYPTOMPK could not only analyze the `crypt` function, but also track and protect the password propagation in these two host programs.

For each program, it took a single graduate student at most 10 to 15 hours (sometimes spread over multiple days) to understand where the labels should be assigned. We believe it

[†] To first generate analyzable non-optimized bitcode, we used the compilation option "`-O0 -Xclang -disable-llvm-passes`" to disable unnecessary optimizations. Next, the generated bitcode is sent to the analysis passes of CRYPTOMPK to find sensitive buffers/operations and the output code is instrumented with our MPK-enabled protection. Finally, we could compile the bitcode into executables with LLVM backend (with the "`-O2`" option to optimize the binary code).

TABLE I: Results of buffer labeling, operation identifying, and code protection

Program	Tags	Total MemOps	Tainted MemOps (declassification)	Tainted MemOps	Total Functions	Crypto Functions	# of Protected Functions				
							Total (HF)	AP	OP	UP	RF
ccrypt	4+3	1049	829	838	70	61	22(19)	19	2	1	30
libsodium	1+1	6513	140	151	930	71	26(21)	25	0	1	31
libhydrogen	2+3	277	57	162	116	62	11(8)	11	0	0	17
Apache+OpenSSL	7+2	92779	0+2149	2528+2223	4879+11082	34+246	0+75(0+66)	75	0	0	177
Nginx+OpenSSL	7+2	70126	0+2149	4439+2223	1347+11082	24+246	0+75(0+66)	75	0	0	177
OpenSMTPD+crypt	2+1	14170	4+492	7+566	892+40	22+33	4+18(0+16)	22	0	0	19
vsftpd+crypt	3+1	9122	9+492	10+566	596+40	42+33	9+18(0+16)	27	0	0	19
Total	**39**	**194,036**	**6,321**	**13,713**	**31,074**	**874**	**296(212)**	**254**	**2**	**2**	**470**

HF: Hotspot functions; **AP**: accurately protected; **OP**: over protected; **UP**: under protected; **RF**: replicated functions for different contexts

will take developers of the application or crypto libraries even less time to perform the labeling.

C. Labeling Accuracy

To evaluate whether CryptoMPK identifies intermediate crypto data and relevant operations accurately, we first executed the protected programs (instrumented with runtime checks) using previously prepared test cases. We found the executed programs passed all test cases without producing a feedback, which indicates that CryptoMPK properly granted permissions to all memory accesses of crypto buffers in tested programs. Then we manually verified the overall labeling results, which are listed in Table I. We observed that both the identified crypto memory operations (**Tainted MemOps (declassification)**) and functions to fulfill crypto operations (**crypto functions)**) are only a small portion of those in the entire programs. Agadakos *et al.* [39] also reported a similar result, which shows 93.82% of code in OpenSSL-libcrypto could be removed in specific application scenarios. This demonstrated the in-process isolation among used and non-used code is expected to reduce attack surfaces significantly.

We found for ccrypt, libsodium, libhydrogen, and crypt with OpenSMTPD and vsftpd, the ciphertext does not get further propagated, then the effect of over-tainting is moderate (**Tainted MemOps** vs. **Tainted MemOps (declassification)**). However, if the ciphertext is further used by other parts of the application (which is the case for Apache and Nginx), we saw a substantial increase of sensitive memory operations that we have to protect, i.e., 2528/4439 extra memory operations. Actually, Apache and Nginx do not access the crypto secret. They delegate the management of crypto buffers to crypto libraries instead. In these cases, the crypto-aware analysis successfully excludes unnecessary code in host programs from accessing sensitive crypto secrets. CryptoMPK also labeled four and nine sensitive memory operations in the application contexts for OpenSMTPD and vsftpd, respectively. We further confirmed these operations in the host programs access the `passwd` buffers and thus should also be protected.

Similar to CryptoMPK, DynPTA [40] labeled 12.79% memory operations as sensitive for Nginx+OpenSSL, while CryptoMPK labeled only 3.06% (2149/70126). Our extended analysis further demonstrated that had CryptoMPK not adopted the crypto-aware analysis (declassification), the labeled memory operations would increase to (4439+2223)/70126=9.5%, which is consistent with the result of DynPTA.

Among all crypto functions, CryptoMPK found 296 (34.3%) of them accessed crypto secrets. As Table I shows, except four functions in ccrypt and libsodium, CryptoMPK accurately protected functions that operated crypto buffers. We additionally examine the over protected (OP) and under protected (UP) functions. We found those functions involve either an external file reading or a random number generation. For file reading functions, CryptoMPK could not determine whether the read content is sensitive and thus under protect them. For random number generation functions, CryptoMPK considers all random numbers used in a crypto application are sensitive and thus over protect them.

CryptoMPK conducted a function level crypto domain isolation for 212 of the 296 protected functions, and conducted instruction level isolation for 84 functions. It followed the strategy mentioned in Section IV-D to choose the appropriate protection granularity. We further invited two experienced players who have participated in DEF CON CTF Finals to help check these functions, and they did not find vulnerable code in those functions. We also counted the number of replicated functions in the last column (**RF**) of Table I to show the necessity of our context-sensitive analysis. The number indicates for all protected functions (**Total(HF)**), how many different contexts are involved (and thus we need to generate a new copy of the function). This allows a fine-grained protection so that we don't have to choose between either "always protect" or "always not protect" a function.

D. Security Analysis

To model the capabilities of attackers who can execute memory corruption based information leak attacks, we adopt the taxonomy proposed by Szekeres *et al.* [41]. By utilizing either an out-of-bounds pointer or a dangling pointer, attackers could access unauthorized memory regions. In response, we illustrate how CryptoMPK defends against attacks using such primitives.

- **Out-of-bounds Pointers.** We assume that an attacker owns an out-of-bounds pointer in non-crypto domain. He can use this pointer to either read data before or after a specific memory region (buffer overflow or underflow respectively), and the pointer can even be used to read content of a designated memory address (arbitrary memory read).

For CryptoMPK protected programs, the isolation guarantees that the operations in crypto domain do not use the out-of-bounds pointer in non-crypto domain. Even if the attacker controls this pointer and could assign it with any memory address of crypto buffers, he cannot use this pointer to access the protected buffers because he lacks the corresponding `PKEY` permission. Therefore, the attacker could not exploit such vulnerable pointers to leak sensitive information.

- **Dangling Pointers.** Similarly, we assume that an attacker owns a dangling pointer in non-crypto domain. CryptoMPK guarantees that this pointer should never point to a crypto buffer because CryptoMPK uses two independent memory managers for crypto domain and non-crypto domain, respectively. A dangling pointer only points to memory buffers of non-crypto domain and thus the attacker could not leak sensitive data using this vulnerable pointer.

Besides confidentiality protection, we also enhance the integrity protection by adding the binary code rewriting of ERIM [42] to eliminate any unintentional occurred `WRPKRU` or `XRSTOR` gadgets, and thus prevent illegal privilege switching caused by code reuse attacks.

E. Protection Effectiveness

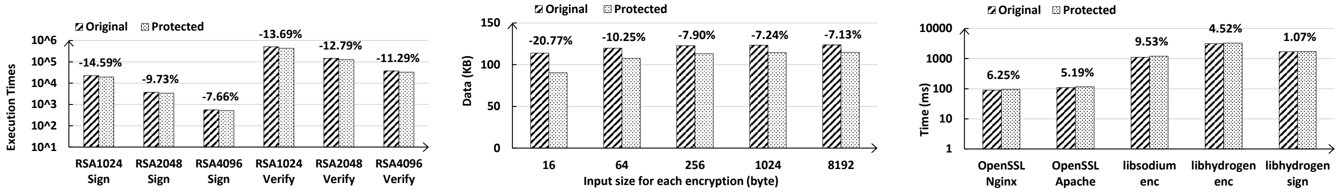
We checked the results of the analysis-driven labeling of CryptoMPK, and found it protected not only crypto keys but also confidential information propagated from the secret keys. We manually examined the protected buffers of each crypto applications to verify whether crucial propagated secrets were protected (details of CryptoMPK labeled code can be downloaded at https://cryptompk.code-analysis.org). For all tested applications, we found propagated secrets were well-protected:

- **SSL/TLS.** Besides private key and session key, CryptoMPK additionally protected crypto operations in 75 functions of OpenSSL, e.g., the RSA `sign` function uses Montgomery modular multiplication [43] to accelerate exponential operation. In this function, the Montgomery transformation of private key components p and q produces several intermediate `BIGNUM` structs, and those buffers are kept on the heap for a long time.
- **AES.** CryptoMPK labeled crypto buffers on either stack or heap for ccrypt. In particular, ccrypt first reads a variable-length key passphrase from the external input, copies the initial secret to a password buffer with specific newline format `key2`, then hashes it into a 16-byte `keyblock`. Next, it executes the standard AES key scheduling to extend the 16-byte `keyblock` to 15 round keys stored in an AES round key array `rkk` (each round key is a 16-byte array). Moreover, all these buffers are not sanitized after the crypto operations. As a result, a memory disclosure of either `key2`, `keyblock`, or `rkk` buffer could give the attacker enough information to recover the AES key and thus decrypt the ciphertext.
- **Chacha20-Poly1305.** Among the labeled crypto buffers of libsodium and libhydrogen, we found specific crypto context structs (e.g., `poly1305_state` for the *chacha20-poly1305* cipher). In further, some functions would propagate the secret key information from a context struct to a local variable. For instance, in the `crypto_secretstream_xchacha20poly1305_rekey` function of libsodium, the secret information propagates to the `new_key_and_inonce` array on the stack. If this array is leaked, the attacker only needs to guess a nonce offset (corresponding to the size of ciphertext) by brute-force to decrypt the encrypted data.
- **Crypt-SHA512.** With the labeled tags, CryptoMPK traversed the code and discovered crypto data in 22 and 27 functions in OpenSMTPD and vsftpd, respectively. An interesting observation is that the developer of `crypt` tried to clean sensitive buffers after the hashing (e.g., the `free_key` buffer). However, this manual sanitization is far from comprehensive and there still exist many unprotected buffers. For instance, the 64-byte `correct_words` array in the API is an intermediate buffer that stores input password and will not be sanitized after the execution. Once the attacker obtains this information, he can then recover the input password.

To prove the necessity of our protection, we additionally chose the following five memory disclosure CVEs to test our protection against different types of memory issues.

- **CVE-2011-4576:** an uninitialized variable vulnerability in OpenSSL which leads to a not properly initialized block cipher padding, and attackers could obtain at most 8191 bytes of uninitialized data on the heap.
- **CVE-2014-0160:** the well-known *HeartBleed* bug of OpenSSL that allows remote attackers to obtain sensitive information from process memory via crafted packets.
- **CVE-2016-2176:** a vulnerability that affects `X509_NAME_oneline` function in OpenSSL. Attackers could use this vulnerability to fulfil out-of-bounds reads and obtain at most 1024KB data on the stack.
- **CVE-2017-9798:** a use-after-free vulnerability in Apache. When attackers send an OPTIONS HTTP request, the server would read data from a freed chunk and may lead to potentially sensitive information disclosure.
- **CVE-2018-16845:** an integer overflow vulnerability in Nginx. Attackers can use a compromised variable to execute out-of-bounds memory access.

Note that the vulnerable versions of Apache, Nginx, and OpenSSL are not compatible with each other, we simulated attacks by first porting those CVEs to our protected versions of Apache/Nginx+OpenSSL (but ONLY protected the annotated secrets), and then utilizing the vulnerabilities to search propagated secrets in process memory. Even though an attack could not directly read the crypto key, it could still retrieve a plentiful of propagated secrets from the process memory and leverage those information to recover the key. For instance, an attack could utilize several of the above mentioned CVEs to access heap buffers and obtain intermediate values of Montgomery modular multiplication. By leaking a special intermediate big number `RR` ($\texttt{RR} \equiv 2^{|p|} \bmod p$, p is one of the secret large primes used in RSA cryptosystem), the attacker could calculate p and then factor the RSA big number to obtain another prime q, and finally recover the entire private key triple (d, p, q) by calculating the modular inverse d



(a) OpenSSL speed test: RSA sign/verify in 10s (b) OpenSSL speed test: AES-GCM (c) Network traffic and file protection

Fig. 4: Runtime overhead of crypto speed tests and crypto applications under the protection of CRYPTOMPK

of e mod $(p-1)(q-1)$.Similarly, attackers could recover AES and Chacha20 keys using intermediate states, and use the intermediate blocks of crypt-SHA512 to recover input password. In response, CRYPTOMPK extensively identifies intermediate crypto buffers and relocates them to protected region, and guarantees the security since memory disclosure attacks cannot recover useful secrets in non-crypto domain.

F. Performance Tests

1) Runtime Overhead: We tested the runtime overhead introduced by CRYPTOMPK by evaluating the performance of protected OpenSSL, libsodium, and libhydrogen libraries. In detail, we tested the slowdown for RSA and AES using `OpenSSL speed test` (a built-in cipher benchmark of OpenSSL), and the overhead of real-world crypto applications by 1) testing HTTPS throughput of Nginx/Apache+OpenSSL with the ApacheBench [44] (both programs were configured to use `ECDHE-RSA-AES128-GCM-SHA256` cipher suite, ApacheBench simulated 20 clients, each sending 1,000 requests); 2) encrypting 100 MB random data with libsodium; 3) signing/encrypting 100 MB random data using libhydrogen.

Figure 4 depicts the overhead for each test case. In Figure 4a and Figure 4b, we found except the less frequently used key-size (RSA-1024) or input-size (AES-GCM encryption with a 16-byte input), the execution slow down is moderate (from 7.13% to 12.79%). This demonstrates the performance impact for most computational intensive crypto algorithms is acceptable. In comparison, Glamdring [31] with a similar code partitioning model suffered from more than 30% slowdown for RSA-4096 sign and about 40% slowdown for AES-CBC-256.

For real-world crypto applications (Figure 4c), we observed a low overhead for a fine-grained isolation: The data encryption with libsodium and libhydrogen suffered 9.53% and 4.52% extra execution time, respectively. And the public key signing of data using libhydrogen only incurred an overhead of 1.07%. In particular, the overhead of HTTPS communication under Apache Benchmark is only 6.25% and 5.19% for Nginx and Apache, respectively. Compared to CRYPTOMPK, ERIM [42] and libmpk [5] that also utilize MPK to protect Nginx+OpenSSL (only protecting the AES session keys) and Apache+OpenSSL (only protecting the RSA private key) introduced an overhead of 5.06% and 4.82%, respectively. Since CRYPTOMPK additionally protects the RSA private key as well as 2,149 memory operations in this case, its MPK-enabled crypto domain isolation is very efficient.

2) Code Bloating: We tested the code bloating effect brought by the code transformation of CRYPTOMPK. Particularly, we measured how crypto code (libraries such as OpenSSL and crypto utilities such as ccrypt) bloat after the protection. After applying CRYPTOMPK to targets listed in Figure 5, we found the code bloating for crypto code is acceptable for cloud servers. For larger targets (OpenSSL and libsodium), the code bloating ratios are less than 20%. For targets with relatively small code base (libhydrogen, libcrypt, and ccrypt), although the code bloating ratios exceed 50%, the actually increased code size is less than 50 KB.

Since the code bloating is mainly due to the function replication (Section III-E3), we counted the number of copied functions (not only the MPK protected ones shown in Table I, but also their callers) for each tested target. We found although the bloating ratios of libhydrogen, libcrypt, and ccrypt are more the 50%, the number of copied functions (59 for libhydrogen, 29 for libcrypt, and 64 for ccrypt) is not large. And for libraries with larger code base, the copied functions only occupied a small portion. For instance, CRYPTOMPK only copied 184 of 11,082 (4% of the entire code size) functions in OpenSSL.

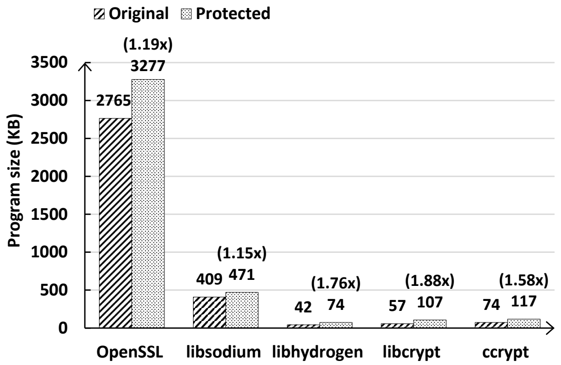


Fig. 5: Code bloating of CRYPTOMPK-protected programs

3) Analysis Costs: We evaluated the costs of static source code analysis by measuring the consumed time of crypto buffer labeling and crypto operations identification. The Results are shown in Table II. Note that for Apache and Nginx, they executed the same APIs of OpenSSL to enable TLS and for each host program only one function is involved. Thus we only consider the analysis time against the code of OpenSSL.

From Table II we observed that CRYPTOMPK could accomplish the analysis of most targets in less than three seconds. The only exceptions are the analysis against the `RSA` implementation of OpenSSL and the password hashing of vsftpd: it took hundreds of seconds for CRYPTOMPK to finish the crypto buffer labeling/crypto operations identification tasks. We checked the analysis procedure and found the reasons.

TABLE II: Analysis performance for each experiment target

Case	**SBL(s)**	**SMOI(s)**	**Total(s)**
libhydrogen	0.31	0.41	0.72
ccrypt	0.97	1.02	1.99
OpenSMTPD+libcrypt	1.41	1.02	2.43
libsodium	2.04	1.81	3.85
vsftpd+libcrypt	244.39	52.91	297.30
{Apache, Nginx}+OpenSSL	638.29	540.94	1179.23

SBL : time of crypto buffer labeling;
SMOI : time of sensitive memory operation identification

TABLE III: Comparison to related systems

System	**C1**	**C2**	**C3**	**C4**	**C5**
Cali [53]	✓	✗	OP	DI	nsjail [54]
ConfLLVM [8]	✗	✗	UP	AI	MPX [55]
DataShield [6]	✓	✗	OP	AI	MPX [55]
Glamdring [31]	✓	✗	OP	DI	SGX [56]
libmpk [5]	✗	✗	UP	DI	MPK [14]
SeCage [7]	✓	✗	OP	DI	VMFUNC [57]
SEIMI [58]	✗	✗	UP	DI	SMAP [59]
Shreds [23]	✗	✗	UP	DI	ARM Memory Domains [60]
xMP [4]	✗	✗	UP	DI	EPTP [61]
CryptoMPK	✓	✓	AP	**DI**	**MPK**

C1: Automated Annotation
C2: Context-sensitive Protection
C3: Propagated Secrets Protection
C4: Isolation Mode
C5: Isolation Feature
AI: Address-based Isolation
DI: Domain-based Isolation
UP: Under-protected
OP: Over-protected
AP: Accurately-protected

For case of OpenSSL, the involved code in OpenSSL is significantly more complex than that of other targets. A particular reason is that OpenSSL implemented more than one versions of *modulus and exponent* algorithms for different platforms. CryptoMPK, however, is path-insensitive and traversed all of them and thus spent a longer analysis time. For vsftpd, the major overhead is due to the analysis of the host program (i.e., vsftpd) rather than the crypt API. Among the 596 functions of vsftpd, 9 of them involve crypto operations, and vsftpd uses two threads to manage crypto secrets separately. Therefore CryptoMPK spent more analysis time. In comparison, the similar analysis against crypt with OpenSMTPD only spends 2.43 seconds in total, since the host OpenSMTPD program adopts a much simpler way to operate crypto secrets.

VI. Related Work

Keeping crypto keys unprotected in memory is dangerous. Attackers could recover the key through code injection or side channel attacks [19], [45]. However, not all memory buffers holding crypto keys are properly sanitized [46]. Actually, K-Hunt [47] examined popular crypto libraries and utilities, and found that recoverable keys widely existed. Micheli *et al.* demonstrated crypto keys could be effectively recovered from partial information [48]. CryptoMPK advances state-of-the-art by considering not only the crypto keys but also their derived secrets. To the best of our knowledge, we are the first to systematically label all kinds of crypto secrets in programs.

A large number of isolation solutions have been proposed to isolate confidential data in memory. We summarized nine most relevant systems and compare them with CryptoMPK in Table III. Among them, ConfLLVM, libmpk, xMP, Seimi, and Shreds only provide isolation primitives, and require developers to manually annotate sensitive data and operations. With only a manual annotation it is difficult to cover all propagated secrets. To automate sensitive data labeling, Cali, Datashield, Glamdring, and SeCage utilize different kinds of data-flow analyses. In particular, Cali leverages program dependency graph to infer the sensitive memory buffers; Datashield utilizes inter-procedural and context-sensitive data-flow analysis to find all the explicitly and implicitly sensitive variables; Glamdring utilizes static data-flow analysis and static backward slicing to find control and data dependencies on the sensitive data annotated by developers; SeCage combines static and dynamic analysis to decompose monolithic software into several compartments and isolates sensitive data. Unfortunately, none of them considers the characteristic of crypto operations to avoid over-tainting issues. In comparison, CryptoMPK implements a fine-grained labeling that are both context-sensitive and crypto-aware to guarantee the precise isolation of crypto secrets.

From the perspective of isolation mode, We categorize systems in Table III in address-based isolation and domain-based isolation groups. Corresponding to their isolation mode, these systems leverage different software and hardware-featured primitives to implement a more efficient isolation. ConfLLVM and Datashield adopt the Intel MPX feature to help isolate sensitive data based on an address-based isolation. For SeCage, SEIMI, and xMP that utilizes different hardware features, they all need to modify system kernel to implement the protection. For Cali and Glamdring, they require to split the process into multiple parts. In comparison, only libmpk and CryptoMPK seldom modifies the execution model and are easy to deploy.

There exist some orthogonal approaches that would enhance the protection of CryptoMPK. We have in fact applied ERIM [42] to enhance the protection of CryptoMPK. Mimosa [49] uses hardware transactional memory (HTM) to ensure that crypto keys are never loaded to RAM chips. It however only protects private keys, and does not track and protect the derived secrets especially those long-term buffers, which is a key difference from CryptoMPK. Wedge [50] and ProgramCutter [51] partition software into least privilege components, and PM [52] could automatically find partitions that have better balance between security and performance. These techniques could retrofit the domain model of CryptoMPK (e.g., supporting more than one crypto domain).

VII. Conclusion

Protecting confidential data against memory disclosure attacks is crucial to crypto applications. In this paper we present CryptoMPK, which automates crypto secrets tracking and implements fine-grained protection for server applications. With the help of CryptoMPK, even a non-expert developer could easily build and deploy binary executables with crypto secrets isolated. Our evaluation show that CryptoMPK provides reliable protection against memory disclosure attacks, and the protection only incurs at most 9.53% runtime overhead for widely used crypto applications.

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REFERENCES

[1] F. A. P. Petitcolas, **Kerckhoffs' Principle**. Boston, MA: Springer US, 2011, pp. 675–675.

[2] T. P. Parker and S. Xu, "**A Method for Safekeeping Cryptographic Keys from Memory Disclosure Attacks**," in Proc. 1st International Conference on Trusted Systems (INTRUST), 2009.

[3] L. Guan, J. Lin, B. Luo, and J. Jing, "**Copker: Computing with Private Keys without RAM**," in Proc. 21st Annual Network and Distributed System Security Symposium (NDSS), 2014.

[4] S. Proskurin, M. Momeu, S. Ghavamnia, V. P. Kemerlis, and M. Polychronakis, "**xMP: Selective Memory Protection for Kernel and User Space**," in Proc. 41st IEEE Symposium on Security and Privacy (S&P), 2020.

[5] S. Park, S. Lee, W. Xu, H. Moon, and T. Kim, "**libmpk: Software Abstraction for Intel Memory Protection Keys (Intel MPK)**," in Proc. 2019 USENIX Annual Technical Conference (USENIX ATC), 2019.

[6] S. A. Carr and M. Payer, "**DataShield: Configurable Data Confidentiality and Integrity**," in Proc. 12th ACM on Asia Conference on Computer and Communications Security (AsiaCCS), 2017.

[7] Y. Liu, T. Zhou, K. Chen, H. Chen, and Y. Xia, "**Thwarting Memory Disclosure with Efficient Hypervisor-Enforced Intra-Domain Isolation**," in Proc. 22nd ACM SIGSAC Conference on Computer and Communications Security (CCS), 2015.

[8] A. Brahmakshatriya, P. Kedia, D. P. McKee, D. Garg, A. Lal, A. Rastogi, H. Nemati, A. Panda, and P. Bhatu, "**ConfLLVM: A Compiler for Enforcing Data Confidentiality in Low-Level Code**," in Proc. 14th European Conference on Computer Systems (EuroSys), 2019.

[9] **OpenSSL**. https://www.openssl.org/. Accessed 2021.

[10] **Apache**. https://httpd.apache.org/. Accessed 2021.

[11] **ccrypt**. http://ccrypt.sourceforge.net/. Accessed 2021.

[12] **The Heartbleed Bug**. https://heartbleed.com/. Accessed 2021.

[13] K. Koning, X. Chen, H. Bos, C. Giuffrida, and E. Athanasopoulos, "**No Need to Hide: Protecting Safe Regions on Commodity Hardware**," in Proc. 12th European Conference on Computer Systems (EuroSys), 2017.

[14] **Protection Keys**. https://software.intel.com/en-us/articles/intel-sdm. Accessed 2021.

[15] Z. Durumeric, F. Li, J. Kasten, J. Amann, J. Beekman, M. Payer, N. Weaver, D. Adrian, V. Paxson, M. Bailey, and J. A. Halderman, "**The Matter of Heartbleed**," in Proc. 14th Internet Measurement Conference (IMC), 2014.

[16] C. Tice, T. Roeder, P. Collingbourne, S. Checkoway, Ú. Erlingsson, L. Lozano, and G. Pike, "**Enforcing Forward-Edge Control-Flow Integrity in GCC & LLVM**," in Proc. 23rd USENIX Security Symposium (USENIX Security), 2014.

[17] Z. Wang and X. Jiang, "**Hypersafe: A lightweight approach to provide lifetime hypervisor control-flow integrity**," in Proc. 31st IEEE Symposium on Security and Privacy (S&P), 2010.

[18] M. Zhang and R. Sekar, "**Control Flow Integrity for COTS Binaries**," in Proc. 22nd USENIX Security Symposium (USENIX Security), 2013.

[19] J. A. Halderman, S. D. Schoen, N. Heninger, W. Clarkson, W. Paul, J. A. Calandrino, A. J. Feldman, J. Appelbaum, and E. W. Felten, "**Lest We Remember: Cold Boot Attacks on Encryption Keys**," Communications of the ACM, vol. 52, no. 5, pp. 91–98, 2009.

[20] M. Lipp, M. Schwarz, D. Gruss, T. Prescher, W. Haas, A. Fogh, J. Horn, S. Mangard, P. Kocher, D. Genkin, Y. Yarom, and M. Hamburg, "**Meltdown: Reading Kernel Memory from User Space**," in Proc. 27th USENIX Security Symposium (USENIX Security), 2018.

[21] P. Kocher, J. Horn, A. Fogh, , D. Genkin, D. Gruss, W. Haas, M. Hamburg, M. Lipp, S. Mangard, T. Prescher, M. Schwarz, and Y. Yarom, "**Spectre Attacks: Exploiting Speculative Execution**," in Proc. 40th IEEE Symposium on Security and Privacy (S&P), 2019.

[22] **PKS: Add Protection Keys Supervisor (PKS) support**. https://lwn.net/Articles/826091/. Accessed 2021.

[23] Y. Chen, S. Reymondjohnson, Z. Sun, and L. Lu, "**Shreds: Fine-Grained Execution Units with Private Memory**," in Proc. 37th IEEE Symposium on Security and Privacy (S&P), 2016.

[24] **Boost C++ Libraries**. https://www.boost.org/. Accessed 2021.

[25] D. E. Denning and P. J. Denning, "**Certification of Programs for Secure Information Flow**," Communication of the ACM, vol. 20, no. 7, p. 504–513, Jul. 1977.

[26] G. Ramalingam, "**The Undecidability of Aliasing**," ACM Trans. Program. Lang. Syst., vol. 16, no. 5, p. 1467–1471, Sep. 1994.

[27] P. M. Gharat, U. P. Khedker, and A. Mycroft, "**Flow- and Context-Sensitive Points-To Analysis Using Generalized Points-To Graphs**," in Proc. 23rd Static Analysis International Symposium (SAS), 2016.

[28] B. Hardekopf and C. Lin, "**Flow-Sensitive Pointer Analysis for Millions of Lines of Code**," in Proc. 9th Annual IEEE/ACM International Symposium on Code Generation and Optimization (CGO), 2011.

[29] A. Machiry, C. Spensky, J. Corina, N. Stephens, C. Kruegel, and G. Vigna, "**DR. CHECKER: A Soundy Analysis for Linux Kernel Drivers**," in Proc. 26th USENIX Security Symposium (USENIX Security), 2017.

[30] G. M. Essertel, G. Wei, and T. Rompf, "**Precise Reasoning with Structured Time, Structured Heaps, and Collective Operations**," Proc. ACM Program. Lang., vol. 3, no. OOPSLA, Oct. 2019. [Online]. Available: https://doi.org/10.1145/3360583

[31] J. Lind, C. Priebe, D. Muthukumaran, D. O'Keeffe, P. Aublin, F. Kelbert, T. Reiher, D. Goltzsche, D. M. Eyers, R. Kapitza, C. Fetzer, and P. R. Pietzuch, "**Glamdring: Automatic Application Partitioning for Intel SGX**," in Proc. 26th USENIX Security Symposium (USENIX Security), 2017.

[32] **jemalloc memory allocator**. http://jemalloc.net/. Accessed 2021.

[33] **GNU libc**. https://www.gnu.org/software/libc/. Accessed 2021.

[34] **libsodium**. https://doc.libsodium.org/. Accessed 2021.

[35] **libhydrogen**. https://github.com/jedisct1/libhydrogen. Accessed 2021.

[36] **Nginx**. https://nginx.org/en/. Accessed 2021.

[37] **vsftpd**. https://security.appspot.com/vsftpd.html/. Accessed 2021.

[38] **OpenSMTPD**. https://https://www.opensmtpd.org/. Accessed 2021.

[39] I. Agadakos, D. Jin, D. Williams-King, V. P. Kemerlis, and G. Portokalidis, "**Nibbler: Debloating Binary Shared Libraries**," in Proc. 35th Annual Computer Security Applications Conference (ACSAC), 2019.

[40] T. Palit, J. F. Moon, F. Monrose, and M. Polychronakis, "**DynPTA: Combining Static and Dynamic Analysis for Practical Selective Data Protection**," in Proc. 42nd IEEE Symposium on Security and Privacy (S&P), 2021.

[41] L. Szekeres, M. Payer, T. Wei, and D. Song, "**SoK: Eternal War in Memory**," in Proc. 34th IEEE Symposium on Security and Privacy (S&P), 2013.

[42] A. Vahldiek-Oberwagner, E. Elnikety, N. O. Duarte, M. Sammler, P. Druschel, and D. Garg, "**ERIM: Secure, Efficient In-process Isolation with Protection Keys (MPK)**," in Proc. 28th USENIX Security Symposium (USENIX Security), 2019.

[43] P. L. Montgomery, "**Modular Multiplication without Trial Division**," Mathematics of Computation, vol. 44, no. 170, pp. 519–521, 1985.

[44] **ApacheBenchmark**. https://httpd.apache.org/docs/2.4/programs/ab.html. Accessed 2021.

[45] K. Harrison and S. Xu, "**Protecting Cryptographic Keys from Memory Disclosure Attacks**," in Proc. 37th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), 2007.

[46] Z. Yang, B. Johannesmeyer, A. T. Olesen, S. Lerner, and K. Levchenko, "**Dead Store Elimination (Still) Considered Harmful**," in Proc. 26th USENIX Security Symposium (Usenix Security), 2017.

[47] J. Li, Z. Lin, J. Caballero, Y. Zhang, and D. Gu, "**K-Hunt: Pinpointing Insecure Cryptographic Keys in Execution Traces**," in Proc. 25th ACM Conference on Computer and Communications Security (CCS), 2018.

[48] G. D. Micheli and N. Heninger, "**Recovering cryptographic keys from partial information, by example**," in Cryptology ePrint Archive: Report 2020/1506 (ePrint), 2020.

[49] L. Guan, J. Lin, B. Luo, J. Jing, and J. Wang, "**Protecting private keys against memory disclosure attacks using hardware transactional memory**," in Proc. 36th IEEE Symposium on Security and Privacy (S&P), 2015.

[50] A. Bittau, P. Marchenko, M. Handley, and B. Karp, "**Wedge: Splitting Applications into Reduced-Privilege Compartments**," in Proc. 5th USENIX Symposium on Networked Systems Design and Implementation (NSDI), 2008.

[51] Y. Wu, J. Sun, Y. Liu, and J. S. Dong, "**Automatically Partition Software into Least Privilege Components using Dynamic Data Dependency Analysis**," in Proc. 28th IEEE/ACM International Conference on Automated Software Engineering (ASE), 2013.

[52] S. Liu, D. Zeng, Y. Huang, F. Capobianco, S. McCamant, T. Jaeger, and G. Tan, "**Program-mandering: Quantitative privilege separation**," in Proc. 26th ACM Conference on Computer and Communications Security (CCS), 2019.

[53] M. Bauer and C. Rossow, "**Cali: Compiler-Assisted Library Isolation**," in Proc. 16th ACM on Asia Conference on Computer and Communications Security (AsiaCCS), 2021.

[54] **nsjail**. https://nsjail.dev/. Accessed 2021.

[55] **Introduction to Intel Memory Protection Extensions**. https://software.intel.com/content/www/cn/zh/develop/articles/introduction-to-intel-memory-protection-extensions.html. Accessed 2021.

[56] **SGX**. Intel(R) 64 and IA-32 Architectures Software Developer's Manual Volume 3C: System Programming Guide, Part 13. Accessed 2021.

[57] **VMFUNC**. Intel(R) 64 and IA-32 Architectures Software Developer's Manual Volume 1: Basic Architecture, Part 5. Accessed 2021.

[58] Z. Wang, C. Wu, M. Xie, Y. Zhang, K. Lu, X. Zhang, Y. Lai, Y. Kang, and M. Yang, "**SEIMI: Efficient and Secure SMAP-Enabled Intra-process Memory Isolation**," in Proc. 41st IEEE Symposium on Security and Privacy (S&P), 2020.

[59] **SMAP**. Intel(R) 64 and IA-32 Architectures Software Developer's Manual Volume 3A: System Programming Guide, Part 4. Accessed 2021.

[60] **ARM Memory domains**. https://developer.arm.com/documentation/ddi0211/k/memory-management-unit/memory-access-control/domains. Accessed 2021.

[61] **EPTP**. Intel(R) 64 and IA-32 Architectures Software Developer's Manual Volume 3C: System Programming Guide, Part 2. Accessed 2021.

[62] **Clang: a C language family frontend for LLVM**. https://clang.llvm.org/. Accessed 2021.

[63] **The LLVM gold plugin**. https://llvm.org/docs/GoldPlugin.html. Accessed 2021.

[64] **Control Flow Integrity**. https://releases.llvm.org/10.0.0/tools/clang/docs/ControlFlowIntegrity.html. Accessed 2021.

Appendix

A. Details of Test Cases

We used two sets of widely used open source projects to evaluate CryptoMPK. The first set contains four crypto libraries and the second set contains four widely used Linux web server programs. Details of the tested libraries and programs are shown in Table IV. The source code of them could be found in https://cryptompk.code-analysis.org. To evaluate whether CryptoMPK can be applied to protect sensitive data in real world applications, we consider four typical application scenarios and tested CryptoMPK with the corresponding cases.

1) **File Encryption.** We employed ccrypt to conduct file encryption/decryption. ccrypt reads the passphrase from a local file and derives its AES encryption key. Then it uses the derived key to fulfil file encryption/decryption.
2) **Message Protection.** We implemented an authentication encryption program using ciphers of libsodium and libhydrogen (i.e., *xchacha20-poly1305* stream cipher and *Curve25519* elliptic curve public key cipher), which fulfils message encrypting and signing.
3) **SSL/TLS Transmission.** We deployed Nginx and Apache with OpenSSL to provide HTTPS service for browsers. We chose the widely used *ECDHE-RSA-AES128-GCM-SHA256* cipher suite for the TLS connection. Note that the analysis for other crypto suites are similar and thus we only tested one of them.
4) **Password Authentication.** We deployed vsftpd and OpenSMTPD with password authentication to provide FTP and SMTP services, respectively. In both applications, the input passwords are verified by the `crypt` password hashing API provided by libcrypt of glibc.

Library	Version	Line of Code
libcrypt	2.27	3,016
libhydrogen	0.2.0	2,597
libsodium	1.0.18	32,279
OpenSSL	1.0.2u	163,734
Application	**Version**	**Line of Code**
Apache	2.4.43	235,956
ccrypt	1.11	21,558
OpenSMTPD	6.0.3p1	39,713
Nginx	1.17.10	137,092
vsftpd	3.0.3	15,052

TABLE IV: The evaluated programs and crypto libraries.

B. Compiling and Analyzing Experimental Targets

In the following, we briefly present the steps of how to compile and analyze our experimental targets. More detailed instructions could also be found in https://cryptompk.code-analysis.org.

To analyze the source code of the tested projects, CryptoMPK needs to first compile source code into LLVM IR bitcode for the following analyses. To implement a cross-module analysis, CryptoMPK merges LLVM IR bitcode modules generated from each source code file into a single bitcode file. It first utilizes the LLVM compiler infrastructure to handle source code in the pre-processing phase (by using the `-emit-llvm` option of Clang [62] to generate a set of LLVM IR bitcode modules). Next, CryptoMPK merges them into a single bitcode file by leveraging LLVM gold plugin [63].

CryptoMPK by default adopts a conservative optimization level (i.e., `-O0` for LLVM) to generate bitcode. Using such a compilation option, all data references in bitcode are in the form of memory reference. We observe that a large number of memory references often lead to unacceptable memory overhead for CryptoMPK in sensitive buffer labeling phase. As a result, CryptoMPK further applies the `mem2reg` optimization pass to transform memory references of function primitive type data to register references. CryptoMPK also applies `jump threading`, `simplifycfg` and `dce` passes to optimize control flow, which will improve analysis performance.

When applying CryptoMPK to complex code bases such as OpenSSL and vsftpd, some execution environments with limited RAM may suffer from out-of-memory issue. We

TABLE V: Performance overhead comparison between CryptoMPK fully-protected programs and their memory re-allocation only counterparts

Test Suite	Baseline	Fully Protected	Memory Re-allocation Only
RSA1024-Sign (sign/s)	2,264.19	1,933.86 (14.59%)	2,066.51 (8.73%)
RSA2048-Sign (sign/s)	373.92	337.52 (9.73%)	344.24 (7.94%)
RSA4096-Sign (sign/s)	55.29	51.06 (7.66%)	51.44 (6.96%)
RSA1024-Verify (verify/s)	50,548.27	43,629.8 (13.69%)	44,251.45 (12.46%)
RSA2048-Verify (verify/s)	14,399.73	12,557.67 (12.79%)	12,612.88 (12.41%)
RSA4096-Verify (verify/s)	3,715.38	3,295.75 (11.29%)	3,298.49 (11.22%)
AES-16 (KB/s)	113,876.33	90,228.85 (20.77%)	103,922.18 (8.74%)
AES-64 (KB/s)	119,801.85	107,516.41 (10.25%)	110,329.25 (7.91%)
AES-256 (KB/s)	122,768.49	113,073.89 (7.90%)	113,779.24 (7.32%)
AES-1024 (KB/s)	123,387.07	114,451.00 (7.24%)	114,776.03 (6.98%)
AES-8192 (KB/s)	123,664.66	114,844.60 (7.13%)	115,042.03 (6.97%)
Nginx (ms/req)	89.81	95.421 (6.25%)	94.73 (5.48%)
Apache (ms/req)	109.14	114.81 (5.19%)	114.03 (4.48%)
libsodium-enc (sec)	1.102	1.207 (9.53%)	1.204 (9.26%)
libhydrogen-enc (sec)	3.122	3.263 (4.52%)	3.189 (2.15%)
libhydrogen-sign (sec	1.686	1.704 (1.07%)	1.696 (0.59%)

suggest that analysts could choose to ignore a certain group of functions to finish the analysis: (i) ASN1-family functions in OpenSSL are related to parsing ASN1 certificate files. Such parsing logic is very complicated, and can leads to path explosion in analysis if not handled. Since they do not propagate any taint tags based on our knowledge, we pruned them off in the analysis; (ii) the built-in dynamic memory management functions in OpenSSL. OpenSSL uses BN_POOL_get to implement stack-like allocation of BIGNUM. However, the static analysis of CryptoMPK cannot deal with memory pool well for CryptoMPK is adopting weak-updating strategy as mentioned in Section IV-B. Hence CryptoMPK handles BN_POOL_get specifically. In sensitive buffer labeling phase, CryptoMPK only allocates object at the first time it traverse into BN_POOL_get. (iii) Error handling function is frequently used in vsftpd, which introduce high analysis costs for CryptoMPK. Empirically, those functions are not vulnerable, we manually disable the analysis against them (e.g. bug die and die2) to improve the analysis performance.

After CryptoMPK finishes all LLVM IR level code transformation for crypto buffer protection, it performs a final pass to optimize the generated IR instructions. Then, the optimized IR code are compiled into binary code, and linked it to a prebuilt shared library that provides secure memory management (i.e., implementing m_malloc and m_free based on Jemalloc) to generate the executables, and we could utilize the binary analysis module of ERIM to check the generated binary code.

C. Evaluation for Performance Overhead of Memory Re-allocation and CFI

Since the overhead of CryptoMPK is not only caused by MPK privilege switching but also by our implemented memory re-allocation, we further measured the runtime performance of tested targets with memory re-allocation only (i.e., disabling MPK privilege switching), and compared it with the performance of fully-protected targets. The result is shown in Table V. We found that the introduced memory re-allocation actually contributed a major part of the entire overhead in most test cases, and this indicates that a further optimized memory re-allocation mechanism could be fulfilled to implement a more efficient protection. We leave this as a future work.

The overhead of CryptoMPK is only related to memory isolation and does not involve integrity protection. To approximately evaluate the overhead of an integrated solution combining CryptoMPK and CFI, we measured the combined performance overhead with both CryptoMPK and the LLVM-CFI [64]. Note that the used LLVM-CFI (version 10.0.1) still introduced compatibility issues for OpenSSL since the crypto library contains many cases of mismatching between a function pointer and its pointed function. We therefore manually disable the CFI for those function pointers in our experiments.

As shown in Table VI, after applying CFI protection, the runtime overhead additionally increased around 2% for our tested targets. This implies the feasibility of combining current CFI mechanisms and CryptoMPK. Nonetheless, we point out that ensuring integrity is still a very challenging problem and is under active research. As a result, CryptoMPK still focuses on the confidentiality aspect only in this paper.

TABLE VI: Results of MPK+CFI Protection

Program	MPK overhead	MPK+CFI overhead
libsodium	11.37%	13.74%
libhydrogen-enc	4.52%	4.52%
libhydrogen-ign	1.07%	1.07%
Apache+OpenSSL	5.19%	7.03%
Nginx+OpenSSL	6.62%	7.69%