Abstract—The EOSIO blockchain, one of the representative Delegated Proof-of-Stake (DPoS) blockchain platforms, has grown rapidly recently. Meanwhile, a number of vulnerabilities and high-profile attacks against top EOSIO DApps and their smart contracts have also been discovered and observed in the wild, resulting in serious financial damages. Most of EOSIOs smart contracts are not open-sourced and they are typically compiled to WebAssembly (Wasm) bytecode, thus making it challenging to analyze and detect the presence of possible vulnerabilities. In this paper, we propose 

\textsc{Eosafe}, the first static analysis framework that can be used to automatically detect vulnerabilities in EOSIO smart contracts at the bytecode level. Our framework includes a practical symbolic execution engine for Wasm, a customized library emulator for EOSIO smart contracts, and four heuristics-driven detectors to identify the presence of four most popular vulnerabilities in EOSIO smart contracts. Experiment results suggest that \textsc{Eosafe} achieves promising results in detecting vulnerabilities, with an F1-measure of 98%. We have applied \textsc{Eosafe} to all active 53,666 smart contracts in the ecosystem (as of November 15, 2019). Our results show that over 25% of the smart contracts are vulnerable. We further analyze possible exploitation attempts against these vulnerable smart contracts and identify 48 in-the-wild attacks (25 of them have been confirmed by DApp developers), resulting in financial loss of at least 1.7 million USD.

I. INTRODUCTION

With the growing prosperity of cryptocurrencies (e.g., Bitcoin), blockchain techniques have become more attractive and been adopted in a number of areas. Due to the limited throughput (e.g., Transaction Per Second, aka TPS) derived from the inherent principle of the Proof-of-Work consensus, traditional blockchain platforms (e.g., Bitcoin and Ethereum) cannot be used to support high performance applications. Researchers have proposed different consensus protocols, e.g., Proof-of-Stack (PoS) [1] and Delegated Proof-of-Stake (DPoS) [2], to resolve the performance issues.

As one of the most representative DPoS platforms and the first decentralized operating system, EOSIO has become one of the most active global communities. EOSIO adopts a multi-threaded mechanism based on its DPoS consensus protocol, which is capable of achieving millions of TPS. The performance advantage of EOSIO makes it popular for Decentralized Applications (DApps) developers. EOSIO has successfully surpassed Ethereum in DApp transactions just three months after its launch in June 2018 [3] and has further increased its dominance by dozens of times after another several months [4]. For example, the transaction volume of EOSIO on average is more than a hundred times greater than Ethereum [5]. As of 2019, the total value of on-chain transactions of EOSIO has reached more than 6 billion USD.

A smart contract is a computer protocol that allows users to digitally negotiate an agreement in a convenient and secure way. In contrast to the traditional contract law, the transaction costs of the smart contract are dramatically reduced, and the correctness of its execution is ensured by the consensus protocol. EOSIO's smart contracts can be written in C++, which will be compiled to WebAssembly (aka Wasm) and executed in the EOS Virtual Machine (EOS VM). Wasm is a web standard specifying the binary instruction format for a stack-based VM, and it can be run in modern web browsers and other environments [6].

However, it is not easy to guarantee the security of the implementation of smart contracts, EOSIO in particular. A number of vulnerabilities have been discovered in EOSIO's smart contracts, while severe attacks have been observed in the wild, which caused a large amount of financial damages. For instance, in fall 2018, a gambling DApp, EOSBet, was attacked twice within just a month [7], [8] due to fake EOS and fake receipt vulnerabilities, causing 40,000 and 65,000 EOS losses, respectively. Therefore, identifying the security issues of smart contracts is necessary to prevent such attacks.

Unfortunately, most smart contracts on EOSIO are not open-sourced, and there are few analysis tools towards analyzing the Wasm bytecode, which makes it more difficult to detect vulnerabilities for EOSIO smart contracts automatically. Although many efforts have been made to analyze the Ethereum smart contracts by the community [9]–[16], none of them, however, can be applied to EOSIO smart contracts, as these two ecosystems are totally different, ranging from the virtual machine, the structure of bytecode, to the types of vulnerabilities.

Specifically, there exists several challenges to analyze EOSIO smart contracts. First of all, EOS VM is more complicated than Ethereum VM in regard to their instructions, including both quantity and variety. For example, EOS VM supports floating point operations, type conversion and advanced jump instructions like \texttt{br_table}. Secondly, compared with Ethereum bytecode, the Wasm bytecode itself is more complicated to analyze because of the multi-level nested structure in functions which leads to a complicated jump relationship between basic blocks. Thirdly, most EOSIO vulnerabilities discovered so far are more complicated than...
previously discovered simple vulnerabilities (e.g., integer over-
flow). Thus it usually requires more semantic information, e.g.,
fields of the platform-specific data structure as the indexes, to
model and analyze them. For example, to detect the fake EOS
vulnerability (described in Section III-A), we need to check
the specific value of argument in function apply.

This Paper. We have implemented EOSAFE, the first sys-
tematic static analysis framework for detecting vulnerabilities
of EOSIO smart contracts. Specifically, we first implement
a symbolic execution engine for the Wasm bytecode, and
mitigate the inherent path explosion problem by applying
a heuristic-guided pruning approach. Second, to analyze an
EOSIO smart contract and simulate its external interactive en-
vironment, we implement an emulator to mimic the behaviors
of key EOSIO library functions that are crucial in vulnerability
detection. Third, we propose a generic vulnerability detection
framework, which allows security analysts to easily implement
their own vulnerability detectors as plugins. In this work, we
have implemented four detectors aiming to detect four high-
profile vulnerabilities in EOSIO, including fake EOS, fake
receipt, rollback and missing permission check (see §III).

To evaluate the effectiveness of EOSAFE, we first manually
crafted a benchmark suite including 52 smart contracts, which
is composed of vulnerable smart contracts collected from
publicly verified attacks and their corresponding patched ones.
Experiment results suggest that EOSAFE achieves excellent
performance in identifying existing vulnerabilities. To measure
the presence of vulnerabilities in the EOSIO ecosystem, we
further applied EOSAFE to all the smart contracts in the
ecosystem (53,666 in total). Experiment results suggest that
security vulnerabilities are prevalent in the EOSIO ecosys-
tem: over 25% of the smart contracts (including historical
versions) are vulnerable, and a large portion of them have
not been patched timely. To further measure the impact of
the vulnerabilities, we collect the transaction records (over
2.5 billion transactions in total), and carefully design a set
of conservative heuristic strategies to identify attacks targeting
these vulnerable smart contracts. We have identified 48 attacks
in total, as well as 183 missing permission check actions. By
the time of this writing, 25 attacks have been confirmed by
DApp developers, which have already caused the financial loss
of over 1.7 million USD.

We make the following main research contributions:

- We propose EOSAFE, the first systematic static analysis
  framework for EOSIO smart contracts, which is capable
  of detecting four kinds of popular vulnerabilities. Experi-
  ment results demonstrate that EOSAFE achieves excellent
  performance.

- We apply EOSAFE to analyze over 53K EOSIO smart
  contracts, and perform the first measurement study of the
  overall ecosystem. We reveal the severity of the security
  issues, i.e., over 25% of the smart contracts have been
  exposed to the threats introduced by these vulnerabilities.

- We have identified 48 attacks and 183 missing permission
  check actions related to the identified vulnerabilities,
  which have caused huge financial loss.

In this section, we will briefly introduce the key concepts
related to the EOSIO platform to facilitate the understanding
of this work. For full details, readers can refer to the official
documents (e.g., [17]) for a systematic illustration.

A. Overview of EOSIO

As the first industrial-scale decentralized operating sys-
tem [18], the DPoS-based EOSIO platform is able to achieve
high performance, i.e., millions of transactions per second,
to efficiently execute complicated DApps in its stack-based
virtual machine (i.e., EOS VM).

Similar to Ethereum, users have to create accounts to inter-
act with the EOSIO platform, i.e., invoking a smart contract
through a transaction. In contrast with Ethereum, however,
EOSIO has implemented a complicated account system to
support advanced management with authorization. Besides, a
transaction may contain one or more actions, which can be
used to perform concrete interactions like transferring the EOS
(i.e., the official currency) tokens between two accounts. Fig 1
shows two ways for a user to transfer EOS tokens to a DApp.

B. EOSIO’s Account System

An EOSIO account is represented as a human-readable
name (up to 12 characters) recorded on the blockchain. EO-
SIO has implemented a comprehensive set of access control
systems. Each account has two default permissions: owner
and active. The owner permission is used to indicate
the ownership of an account, and it can be used to restore
other permissions, that may be compromised. The active
permission can be used to transfer tokens or vote for block
producers. Besides these two default permission names, an
account is allowed to create and define new permissions
and their permitted behaviors. In EOSIO, the statement re-
quire_auth(account) asserts if the caller in accordance
with the argument account and has the proper permission.
However, a user can grant its active permission to a DApp
as the situation shown in Fig. 1(a). In this case, the DApp
can invoke actions on behalf of the user with permission
actives.

On the other hand, granting permission is a risky behavior,
because a grantee can do anything with the granted permission.

Fig. 1. Transfer token from a user to a DApp.
Listing 1. An example of apply Function.

C. EOSIO’s Transactions

As the basic unit to form a transaction, an action in EOSIO can invoke a function inside of a smart contract. In EOSIO, the send_inline function is responsible for invoking a new action at the current transaction. Besides, in the EOSIO smart contract, the owner can implement an action handler to determine what to do if an action is received. Within such an action handler, it is possible to trigger another action to a designated account.

Note that any failure in the action/transaction may result in a revert operation. In EOSIO, there are two revert rules whose difference must be taken into account. Specifically, if any action in a transaction terminates accidentally, the transaction will be reverted, and the related state changes will be reset. However, the revert of a transaction will not affect other already on-chain transactions in any case. Unfortunately, the subtle discrepancy might be inadvertently ignored by the developers, which would be vulnerable to attack.

Besides, the developers are permitted to notify others by statement require_recipient as depicted in §II-B. The apply function of each smart contract is responsible for the reaction to handle such a notification. A conventional apply function is shown in listing 1.

As shown in listing 1, apply can be seen as an intermediate function and a dispatcher. It listens for all incoming notifications and invokes the corresponding function of the contract according to the action name. Additionally, in line 1, these three arguments are critical, i.e., receiver, code, and action. When a user sends an action to the network, it addresses a single contract account (the code) and action on that account explicitly. However, the contract can use require_recipient to notify another account so that the contract on that account may respond. When it does this, the code does not change to distinguish the ambiguity between receiving an action directly or from others relay. The receiver is always the account who receives the action.

D. EOSIO’s Smart Contract and Virtual Machine

Usually, DApps developers first use C++ to write smart contracts for EOSIO, and then compile the source code to the WebAssembly (aka Wasm) bytecode, which will be executed in EOS VM. Note that Wasm is a binary instruction format for a stack-based virtual machine. Although it is designed to be an open standard to enable high-performance web applications, it can also be used to support other environments. Due to its efficiency and portability, lots of blockchain-based smart contracts natively support or are open to apply Wasm as the target of compilation, e.g., EOSIO [18], Ethereum [19], Harmony [20], and Polkadot [21].

In more detail, an EOSIO Wasm file is always called a module instead of a program. Inside a module, numerous required or optional sections exist. Here, we show several essential sections:

- **Function.** Declare indexes for each function, which are used later at the Code section.
- **Memory.** It defines the initial memory size of a module and optionally how large it is expected to expand to.
- **Element.** Functions indexes places inside this section can be considered as entries for the current module.
- **Code.** It is the body of the function composed of a sequence of low-level instructions and following the same order of the function indexes in the Function section.
- **Data.** String literals used in the module are often stored in this section and utilized to initialize the Memory area.

Like Ethereum VM, EOS VM supports Stack, Local, and Global, which are pushed and popped from a virtual stack by several instructions (such as local_set, global_get). Also, EOS VM has an area called Memory, a random-accessible linear array of bytes which is encoded by little-endian. This area can only be accessed by using specific instructions, including load and store and their variants.

As usual, EOSIO only stores compiled contract bytecode on the chain instead of the source code. The EOS MainNet is public, thus anyone can obtain Wasm bytecode of any contract through the JSON-RPC API. An EOSIO account, however, can be perceived as a regular account to store tokens and a smart contract simultaneously. But it is not free. EOSIO asks the owner to mortgage some tokens in exchange for an account name. According to our dataset, as of this writing, only around 5,500 smart contracts are deployed by and stored in their accounts, which is far less than that in Ethereum. Nevertheless, in contrast to Ethereum, EOSIO’s smart contract
can be updated in place instead of creating another account and redeploying.

III. VULNERABILITIES IN EOSIO SMART CONTRACTS

In this section, we will introduce representative vulnerabilities that have been exploited by an increasing number of high-profile attacks resulting in financial losses in recent years.

A. Fake EOS

When a user transfers the EOS tokens to a DApp, the balance table of its issuer, i.e., the official account eosio.token, has to be updated. As only eosio.token itself is entitled to perform the update, the user has to invoke the transfer function in eosio.token to request the update, as shown in Fig. 1(b). Once completed, eosio.token will notify the payer and payee (i.e., the DApp) to perform the rest of the original procedure.

Vulnerability Description. The attacker could duplicate the open source eosio.token contract, and issue a token using the same name as the original EOS tokens whose balance table is maintained in the faked eosio.token. When the attacker transfers the fake EOS tokens to the DApp, the only difference is the code field in transaction (see §II-C). If the DApp’s apply function does not verify the issuer, i.e., code is eosio.token instead of other accounts, before entering the transfer function, the fake EOS tokens would be passed in to continue executing the remaining code logic. Finally, the attacker can bypass the DApp’s apply function with his worthless fake tokens.

To mitigate the issue, some DApps narrow down the options of accepted code as shown on line 9 of Listing 1. Unfortunately, if the attacker directly invokes the transfer function of the DApp, the condition code == receiver will be satisfied. In this case, the DApp’s transfer logic is compromised even without the participation of an issuer account, which can be seen as a variant case.

As the above two cases are both related to fake EOS tokens, in this work we name both of them as fake EOS vulnerabilities.

B. Fake Receipt

Apart from the token issuer, the defective verification related to the receipt may still result in another type of attack, as the second round attack EOSBet suffered [7].

Vulnerability Description. If a DApp does not check the receipt properly on receiving a notification, it might be deceived by the attacker that plays the dual roles (accounts) of an initiator and an accomplice at the same time. Specifically, the initiator invokes a normal transfer as the payer, and the accomplice becomes the payee (indicated by to, the argument of the transfer function). When accomplice is notified by eosio.token, it will immediately forward the notification to that DApp without modification. As code (i.e., the argument of the apply function) of the notification (i.e., eosio.token) remains unchanged after being forwarded, the code validation we mentioned in §III-A is satisfied.

However, to of the notification points to the accomplice rather than the DApp in this case. If the DApp does not have proper verification (i.e., with condition self == to), the initiator and the accomplice work together to cheat it into executing the code logic to handle receiving the money transferred from a normal user. In this paper, we use fake receipt vulnerability to represent such bugs.

C. Rollback

The function transfer and reveal can be viewed as the kernel components of a gambling DApp. In the transfer function, DApp handles the bet which is received along with the player’s transfer. In the reveal function, the developer often uses various on-chain state values as seeds (e.g., tapos_block_prefix) to generate pseudo-random number [7] and finally obtains the outcome by comparing the generated number with the player’s input. Note that, we only consider the rollback cases in the gambling DApps, and assume that the reveal function is always there and is reachable from the the entry point (i.e., the apply function) for every gambling DApp due to the essence of the game.

Vulnerability Description. Unfortunately, the above code logic of the reveal function makes all the actions are located in a single transaction, which causes the revert operation can be abused to launch attacks. Specifically, as demonstrated in Fig. 2 an attacker can deploy an evil contract worked as the intermediate between the DApp and eosio.token. The attacker will first invoke the transfer function of the evil contract, which will further initiate the EOS tokens transfer to the DApp. Then, once the evil contract is notified by eosio.token, all the above actions are located in a single transaction. The key point of the evil contract is to keep track of the balance change and respond accordingly when receiving a notification from eosio.token. After checking the balance between before and after the game playing, the evil contract could decide whether to rollback the whole transaction through a revert operation. Namely, if it loses, all the smart contract states and balance table will be reverted to the original, and this transaction will not be recorded on the EOS MainNet. Consequently, the attacker can repeat the procedure until the winning. Such a collision-like operation

1In EOSIO, the uniqueness of token symbols is not required.

2The “pseudo” is due to all these seeds values are deterministic for lack of a true randomness source on blockchain temporarily.
allows the wicked player to arbitrage almost without any cost, which we name it as rollback vulnerability.

D. Missing Permission Check

As said in §II-B in EOSIO, a developer can use require_auth(account), require_auth2(account, permission), and has_auth(account) to check whether the caller equals account and has the proper privileges. For instance, as shown in listing 2 a contract can grant permission to trusted accounts. If an arbitrary account calls B_Func, the condition in line 3 must be satisfied (with condition code == self, where self points to receiver), namely, anyone can call B_Func directly. However, only admitted accounts can pass the assertion of require_auth(receiver) in line 10.

Vulnerability Description. Therefore, imaging a malicious account calls this function while there is no authority requirement in it, the attacker can enter it effortlessly and perform some operations if possible, e.g., modifying the database or calling functions of other contracts in the name of the vulnerable contract. As such, this kind of absence of permission authorization is called missing permission check vulnerability.

```c
void apply(uint64_t receiver, uint64_t code,
    uint64_t action) {
    auto self = receiver;
    if(code == self) {
        B_Func();
    }
}
void B_Func() {
    // the permission check
    require_auth(receiver);
}
```

Listing 2. An example of using permission check at line 10.

IV. TECHNICAL CHALLENGES AND OUR SOLUTIONS

Take all the factors into account, we would like to design and implement a symbolic execution based static analysis system to detect vulnerabilities for EOSIO smart contracts. To recover more semantic information, we use the heuristic-based symbolic execution to perform the in-depth analysis. Namely, semantic information will be presented in the constraints generated by symbolic execution along the paths being analyzed. As a result, we are able to use those constraints as patterns to identify vulnerabilities in smart contracts.

However, no available symbolic analysis framework could be used to handle the EOSIO Wasm bytecode, to the best of our knowledge. Technical challenges exist to realize the proposed system. On one hand, it is known that symbolic execution based solutions may suffer from inherent shortcomings, path explosion in particular. On the other hand, when applied to the vulnerability detection for EOSIO smart contracts, there does exist platform-specific issues, including memory overlap and external/system library dependency, which inevitably affect the effectiveness of the symbolic execution. We will discuss the details in the following.

A. Path Explosion

In EOSIO, this issue is mainly due to two circumstances: executing conditional jump instructions (such as br_if) or invoking function call. Specifically, unlike a normal conditional jump instruction that only generates two new branches, br_table in EOSIO, however, takes an array whose elements are pointers of destination as the argument. As a result, a single br_table can lead to n new branches, where n is the length of the array. Apart from those conditional jump instructions, a function call also imposes a mass of new branches to represent all possible callees. Obviously, the number of branches will increase exponentially if there exists a deep call stack. Unfortunately, a concatenation of several deep call stacks is common in EOSIO smart contracts (DApps in particular). As such, the traditional symbolic execution solutions are not feasible to mitigate the issue.

Accordingly, we adopt a heuristic-guided pruning approach (see §V-A) to serve the need. On one side, we rely on several general pruning strategies based on our hands-on experience to mitigate the issue derived from branches and deep function calls. For example, our operational observation suggests that discarding paths under a specific depth threshold, which is determined by the scenario, will not influence the precision of results for (almost) all cases. Specifically, we expose 1) an option named call_depth, which limits the depth of call stack; and 2) an option named timeout for users to limit the process of symbolic execution.

B. Memory Overlap

The memory area of Wasm can be regarded as a vector of uninterpreted bytes [22], which means users can interpret these raw bits whatever they want through load and store with different value types. The traditional way to emulate memory area is to use linear array, but it wastes a lot of space due to mimic the sparse memory layout of the EOSIO smart contract. Therefore, we decide to use key-value mapping to emulate the memory, where the key is a tuple to specify the address range, and the value is the data being stored, as follows:

(lower-bound, upper-bound) → data

However, this strategy may lead to the memory overlap problem (see Fig. 3). If we use the mapping without optimization, keys (A + 2, A + 3), (A + 3, A + 4), and (A + 2, A + 4) can all be stored directly with no conflicts. As a result, if we retrieve data with the key (A, A + 4), there exists two cases meet the condition (case 1 and 2 shown in Fig. 3), which may
result in retrieving wrong data. Additionally, in case 3, if we want to update data in \((A + 1, A + 3)\), we have to traverse the key space to determine if there is only one entity containing the address range we provided, which must be guaranteed to ensure data consistency. And in case 4, we have to concatenate adjacent stored data chunks to determine how to load data in memory area. In nutshell, all these problems are due to the overlapping memory and improper mapping strategy.

We propose a memory-merging method (see §V-A2) to solve the problem by merging allocated memory. As aforementioned, Wasm provides over 20 memory access related instructions. Thus, we will first create key-value mappings for all of the store-related instructions we encountered, where the values are the stored data in bits. After that, we are able to handle the cases when two keys’ range are adjacent or overlapped according to the proposed memory-merging algorithm, which will update the corresponding data chunks to make sure the precision of execution. In brief, we make the every effort to guarantee that the interval between any two arbitrary keys is a least one bit. By doing so, we successfully overcome the challenge raised in Fig. 3.

C. Library Dependency

To facilitate the development of smart contracts, EOSIO allows the import of external functions as libraries, which means the bodies of these imported functions will not be compiled into Wasm bytecode. EOSIO officially provides plenty of such functions as the system library for DApp developers, and a number of library functions have been imported and used in many (if not most) smart contracts. As such, our analysis will be improperly terminated due to the lack of bodies of those imported function calls.

To resolve the dependency, we have proposed an on-demand and semantic-aware approach (see §V-B) to perform the imported functions emulation. We only focus on functions whose functionality and side effect are related to our analysis. We have to emulate such functions properly to guarantee the correctness of the final result. The strength and coverage of the emulation depend on our need to perform the analysis. Some of the functions, we have to cover the arguments, return value and side effect. For instance, the memory-related function, memmov, in which we have to consider all its side effect on symbolic memory. While some others we may only have to consider the possible side effect. For example, for those table-related functions which has no return value and no effect on vulnerability detection, e.g., db_store_i64, we can just balance the stack without mimic its behaviors.

V. SYSTEM DESIGN

Fig. 4 depicts the overall workflow and architecture of EOSAFE, which takes the Wasm bytecode of an EOSIO smart contract as the input and eventually determine whether the bytecode is vulnerable or not. Specifically, EOSAFE is based on Octopus [23], a security analysis framework for Wasm module, to launch the preprocessing. Each collected smart con-tract will be sent to Octopus to build its corresponding Control Flow Graph (CFG) with the disassembled Wasm instructions.

EOSAFE is mainly composed of three modules, i.e., Wasm Symbolic Execution Engine (Engine for short), EOSIO Library Emulator (Emulator for short), and Vulnerability Scanner (Scanner for short). As shown in Fig. 4, the input after preprocessing (CFGs) are fed to the Scanner to perform vulnerabilities detection in two-step process (locating suspicious functions and detecting vulnerabilities) with the Engine and Emulator. Specifically, the Engine performs the symbolic execution accordingly along with path constraints, which will be used by the Scanner to perform the vulnerability detection. Additionally, the Engine requests Emulator to implement the modeled behaviors when the Engine encounters the call for imported functions. Notice that the challenges discussed in §IV-A and §IV-B are addressed in §V-A, and the challenge discussed in §IV-C is addressed in §V-B.

A. Wasm Symbolic Execution Engine

It is designed as a generic platform to imitate the execution of a smart contract on the stack-based EOS VM. It accepts the CFGs and the disassembled Wasm instructions as the input, and symbolic executes instructions within basic blocks in order for all feasible paths. During the process, the path constraints are generated accordingly. Specifically, the module has to maintain two crucial components: path tree and state. For the path tree, we not only record the constraints generated by symbolic execution, but also all the arguments and return value of imported functions along the path, which contribute to analysis of vulnerabilities detection. As to the state, we maintain some necessary state-related information, including local/global variables, linear memory, stack, and the subsequent instructions with its corresponding program counter.

Specifically, we have addressed the technical challenges mentioned in §IV-A and §IV-B towards the design of the Engine, as follows:
Algorithm 1 Memory-merging algorithm.

**Input:** sm - symbolic memory, dest - insert position, len - data length, data - data

**Output:** sm - updated symbolic memory

**Description:** es and ee respectively stand for lower-bound and upper-bound of address range of the picked key. The o in os and oe stands for the overlapped.

1. **procedure** MEMORYMERGE(sm, dest, len, data)
2. if ¬isOverlapped(sm, dest, len) then
   3. data ← ToLittleEndian(data, len)
   4. sm[dest, dest + len] ← data
   5. else
   6. os, oe ← CalcOverlap(es, ee, dest, len)
   7. UpdateOverlappedPart(sm, os, oe, es, ee)
   8. CatOtherParts(sm, os, oe, es, ee)
   9. keys ← SortKeys(sm)
   10. while i + 1 < len(keys) do
   11. currentKey ← keys[i]
   12. nextKey ← keys[i + 1]
   13. if currentKey[1] == nextKey[0] then
   14. Merge(sm, currentKey, nextKey)
   15. else
   16. RemoveKeys(sm, currentKey, nextKey)
   17. InsertNewKey(sm, currentKey, nextKey)
   18. i ← i + 1
20. return sm

1) **Alleviating path explosion:** We provide two options, including call depth and timeout, for users to mitigate this issue by scarifying the accuracy.

On one hand, as the name suggests, the option call depth is used to confine the depth of the call stack to prevent the analysis from getting into trouble to deal with complicated branches or deep function calls. As we all know, a single function could have several set of constraints corresponding to feasible paths within the function, which may lead to an exponential growth of the number of paths. Thus we limit the depth of call stack to raise the coverage. On the other hand, we may still in trouble when encountering some cases which are extremely time-consuming. To guarantee the process of the whole system, the Engine offers another option named timeout to control the maximum execution time for the path-level analysis. Of course, the timeout results will be recorded for further investigation.

2) **Eliminating the memory overlap:** We implement a symbolic memory to represent the memory of Wasm, and thereby propose a memory-merging algorithm (see Algorithm 1) to emulate the store instruction. This algorithm takes the symbolic memory, address, length of data in byte and data as the input, and finally returns a merged symbolic memory without overlapped/adjacent keys as the output. Specifically, given a new key that will be stored, we will check whether the address range of an existing key is overlapped with that of the new key or not. If so, the insertion will be performed directly; or otherwise, it will update the overlapped part accordingly and concatenate the non-overlapped parts together.

Besides, the keys are sorted in ascending order of the starting position. If two adjacent keys are not overlapped, they will be merged together to form a new key-value pair. For example, the existing key-value pairs are:

**symbolic memory := \{(0, 2) ↦ a_0|a_1, (3, 4) ↦ a_3\}**

When \((2, 4) ↦ a_2|a_3\) arrives, it will update the overlapped part and concatenate the non-overlapped part on necessary:

**symbolic memory := \{(0, 2) ↦ a_0|a_1, (2, 4) ↦ a_2|a_3\}**

After that, it will merge the adjacent keys together:

**symbolic memory := \{(0, 4) ↦ a_0|a_1|a_2|a_3\}**

In brief, this algorithm guarantees the data consistency by forcing all valid addresses appear only once in the key space. Consequently, we are able to solve all the issues raised in Fig. 3 effectively.

B. **EOSIO Library Emulator**

We use the on-demand and semantic-aware approach to resolve EOSIO library dependency. We have manually analyzed the smart contracts of top-100 popular DApps and existing known vulnerable smart contracts (see §VII-A1) to extract all the imported functions from their Function section (see §II-D). Then, we classify all the imported functions into five categories according to their main functionalities (as shown in Table I) to conduct the emulation. Lastly, we can retrieve the side effects from the emulated imported functions. Specifically, the emulating approaches for imported functions of each category in Table I and the corresponding side effects are summarized in the following.

**Blockchain-state functions.** These functions return constants related to the blockchain system, which are mostly used by the smart contracts, as the seeds, to generate the pseudo-random numbers. As there does not exist any side effect, we just emulate them by directly returning a symbolic value to represent the blockchain state.

| Category      | Imported Function Examples                                      |
|---------------|-----------------------------------------------------------------|
| blockchain-state | tapos_block_num, current_time                                    |
| memory-related  | memcp, memset, memmov                                           |
| control-flow-related | eosio_assert, eosio_assert_code                                 |
| authority-related | require_auth, require_auth_2, require_auth_v2                  |
| table-related   | db_get, db_set                                                  |
**Memory-related functions.** As the name suggests, functions in this category are related to the symbolic memory we have implemented. Therefore, we imitate the behaviors as their original intention, and apply the memory-merging algorithm when inserting the new data. Note that, we throw an exception for undefined behaviors, e.g., the negative length of the `memcpy` function due to the constraint solving.

**Control flow related functions.** These functions are those which may alter or terminate the control flow of a smart contract according to their return results. Therefore, we will fork two paths if necessary. For example, two paths will be generated if the predicate of the `eosio_assert` function is a symbolic value rather than a specific boolean value.

**Authority-related functions.** As the authority system is merely related to the detection of missing permission check vulnerability, we only have to examine the existence of these functions without concerning about the specific permission. Hence, we just return a symbolic value to balance the stack.

**Table-related functions.** There is a special data structure in EOSIO that allows for persistent storage of data. Similar to the concept of storage in Ethereum, this kind of data is saved on the blockchain which is called table. Table can be regarded as a database that supports CRUD operations (i.e., Create, Retrieve, Update and Delete) by several platform-specific instructions. For these functions, we only have to focus on the side effects to the memory rather than the internal operations. Specifically, we have implemented some of these functions with return values that will be used to update the memory, as follows:

\[ A = db\_get\_i64(itr, data, length) \]

\[ i64\_store(base, A) \]

Note that, some table-related functions without any return value but only have effect on the table (e.g., `db_update_\_i64`) are the keys for our heuristic strategy, and we need to return the symbolic value of them to balance the stack as well.

C. Vulnerability Scanner

To detect multiple vulnerabilities, the Scanner is designed to be a generic framework to perform the detection. It mainly consists of two steps, i.e., locating suspicious functions and detecting vulnerabilities. In this module, we have integrated four detectors to detect the four most popular vulnerabilities introduced in §III.

For the sake of following discussion, we define the valuable functions as those that invoke imported functions which are capable of affecting the on-chain state, e.g., `send_inline` and `db_update_i64`. Accordingly to our observation, these valuable functions can be heuristically regarded as target functions in some cases, which can significantly reduce the analyzing time. Consequently, in favor of CFG and path tree (composed of constraints and valuable functions), we can identify vulnerabilities efficiently and accurately.

1) Fake EOS: As discussed in §III-A, the validation of code in the `apply` function is necessary to prevent the fake EOS vulnerability. Accordingly, as shown in Algorithm 2 (see Appendix-A), this detector first locates the `apply` function as the suspicious target. After that, it traverses all the feasible paths generated by symbolic executing the `apply` function.

For each group of the constraints corresponding to a feasible path, it will verify two conditions: 1) the variable action points to the `transfer` function (i.e., `action == transfer`); and 2) the variable `code` is not used to perform any checking. If both conditions are met, it will further determine whether the transfer operation was invoked via `indirect_call` or `internal_call` along the current path. However, our investigation shows that not all `transfer` functions are able to affect the on-chain state, and we only focus on those valuable `transfer` functions (line 8 of Algorithm 2). In summary, if all the above conditions are met, then the smart contract can be considered to be vulnerable to the fake EOS vulnerability.

To accelerate the analysis, the Engine will terminate irrelevant paths in advance to avoid further execution. Specifically, early termination will take place if there exists any constraint containing the condition `action == ¬transfer`, which will not affect the detection result.

2) Fake Receipt: As discussed in §III-B, to prevent the fake receipt vulnerability, the contract must verify the recipient of money transfer in the `transfer` function. Specifically, as shown in Algorithm 3 (see Appendix-A), this detector is to locate all the suspicious `transfer` functions (line 3 of Algorithm 3) by first identifying the `apply` functions, and then enumerating all the relevant basic blocks to verify their jump targets whose indices may point to the corresponding `transfer` functions. The reason of doing so rather than locating the `transfer` function directly (like the way to handle the `apply` function in the previous §V-C1) is to avoid the extra burden of the symbolic execution resulting from the complicated computation to determine the `transfer` function. The experimental result shows that the strategy successfully identify the `transfer` functions precisely.

After collecting all the constraints for all target functions, we will verify whether they are vulnerable. Specifically, for a given function, if any constraint of that function is labeled as “transfer”, then the function can be checked directly. Otherwise, it implies that the logic of the `transfer` function might be inlined into the `apply` function. Therefore, we will recover the `transfer` function indicated by a constraint action == `transfer`. Again, here we merely focus on the valuable `transfer` function. As a result, if these recovered `transfer` functions are not protected (with the condition `self == to` as mentioned in §III-B), we will flag the fake receipt vulnerability to this smart contract.

Furthermore, similar to the fake EOS detection, this detector also applied the early termination to accelerate the analysis by avoiding further execution. As the condition `self == to` must be verified either at the entry of the function `transfer`, or before updating changes for related on-chain states, it is
reasonable to terminate the analysis when encountering the invocation of the send_inline function along the path, and turn to analyze the next path instead.

3) Rollback: The reveal function in gambling DApps is often used to generate a random number to determine the result of the current round of the game. Unfortunately, different ways of implementing the reveal function may lead to the risk of being exploited by the attackers. Therefore, this detector first aims to locate all the suspicious reveal functions. Specifically, in an ordinary gambling DApp, the reveal function must apply the send_inline function to invoke the eosio.token's transfer function to transfer reward to the winner. As a result, we can identify all the blocks which contain the statement send_inline to further locate the reveal functions.

Most DApps rely on the reveal function to generate a random number to determine whether the player wins or not. As the modulo calculation (i.e., through the instruction rem) is indispensable, it can be used to extract the random number generator. As shown at line 5 of Algorithm 4 (see Appendix-A), we will remove all the rem instructions generated by EOSIO official libraries, e.g., eoslib, to reduce the false positive. For the remaining instructions, we extract their operands to perform the further analysis by following the rules between line 6 to 11. Specifically, the operand of the dividend of the rem instruction is (partially) composed of any chain state variables, e.g., tapos_block_num, current_time, and transaction_id, we are able to confirm this contract is vulnerable to the rollback vulnerability.

This detector is more complicated than the above two detectors, which inevitably introduces computational burden, i.e., sometimes the send_inline function are too deep for the Engine to reach. As it is not necessary to consider the reachability of the send_inline function of a path (see II-C), we are able to apply two heuristic strategies to accelerate the process to mitigate the issue. Specifically, the first strategy is to traverse feasible paths on demand. Instead of enumerating all paths, we only examine paths that can be used to resolve the data/variable dependency of the target send_inline function. On the other hand, the second strategy is to reduce the size of the path set being examined by the Engine after extracting suspicious functions, namely, removing redundant paths whose basic blocks are thoroughly the subset of other paths. Consequently, we can achieve the smallest path set to cover as much as possible basic blocks.

4) Missing Permission Check: As discussed in II-D, we focus on those functions that are lacking of authority validation, and can be dispatched through the apply function. Therefore, this detector needs to locate the apply function as well. Specifically, it will first traverse all the feasible paths to find out those which allow the user to invoke any invocable function of that smart contract indicated by the variable receiver. Namely, those functions (indexed in Element section of the Wasm bytecode, as explained in II-D that are called along the paths will be regarded as suspicious ones. After that, we will traverse these chosen paths to determine if they are valuable to be exploited without verify the authorities. Consequently, a smart contract, whose valuable functions can be triggered without any permission check, is vulnerable to the missing permission check vulnerability.

VI. IMPLEMENTATION AND EXPERIMENTAL SETUP
A. Implementation

We take advantage of Octopus to construct the CFG of Wasm bytecode, and use z3 solver (version 4.8.6) as our constraint solver. All the other major components of the system, including Wasm Symbolic Execution Engine, EOSIO library Emulator and Vulnerability Scanners are all designed and implemented by ourselves. The implementation is based in Python, which is more than 5.5k lines of code.

B. Experimental Setup

Our experiment is performed on a server running De- bian GNU/Linux with four Intel(R) Xeon(R) E5-2620 v4 @ 2.10GHz and 64G RAM. As aforementioned in §V, the Wasm engine of EOSafe has provided two configuration options (i.e., call depth, and timeout) to address the path explosion issue. During our experiments, we empirically set the call depth as 2 layers, as we find it is enough to identify most vulnerabilities. As to the exploration time, we empirically set the upper bound as 5 minutes, with the following two main reasons. First, within 5 minutes, all the smart contracts in our benchmark can be fully analyzed and detected with promising results (see §VII-A1). Second, as we seek to apply EOSafe to all the smart contracts in the EOSIO ecosystem to characterize the presence of vulnerabilities, we have to make a trade-off between accuracy and scalability. Therefore, the exploration time for each contract is 5 minutes. Note that, all these settings could be easily configured and customized in our tool, to fulfill the different requirements.

C. Research Questions

Our evaluation is driven by the following research questions.

RQ1 How accurate is EOSafe in detecting vulnerabilities of EOSIO smart contracts? It is important to first evaluate the effectiveness of EOSafe on detecting the four vulnerabilities using a reliable benchmark dataset.

RQ2 Are these vulnerabilities prevalent in the ecosystem? It is still unknown to us the severity of the vulnerabilities in the ecosystem. For example, how many smart contracts are vulnerable? How many of them have been noticed and patched by developers?

RQ3 How many smart contracts have been exploited by attackers and what are the impacts of these attacks? After identifying the vulnerable smart contracts, it is worthwhile to investigate the attack events and the corresponding financial loss.

To answer RQ1, in the absence of established benchmarks in the research community, we propose to collect real-world attacks and manually examine the victim smart contracts to craft a reliable benchmark. To answer RQ2, we collect all the available smart contracts on EOSIO and their historical
versions. Then we apply EOSAFE to detect the presence of security vulnerabilities, and characterize the evolution of vulnerabilities. To answer RQ3, we further collect all the on-chain transactions related to the flagged vulnerable contracts, and then propose heuristics to pinpoint possible attacks.

VII. EXPERIMENTAL RESULTS

A. RQ1: Accuracy of Vulnerability Detection

1) Benchmark: As aforementioned, to evaluate EOSAFE, we first make efforts to craft a benchmark that we make available to the community. EOSIO attacks were reported from time to time. Thus, we resort to the security reports released by well-known blockchain security companies and security forums to collect all the related publicly verified attacks [24], [25], as the ground-truth. We have collected 38 attacks related to the vulnerabilities we studied, targeting 34 unique vulnerable smart contracts in total. Note that although these attacks were confirmed by corresponding DApps’ official team and categorized into these four types by security companies, we found that some attack events are irrelevant to smart contract itself but the other external factors, e.g., the server’s issues [26]. Thus, we further manually examined all the involved smart contracts to label their vulnerabilities. Specifically, we found that 3 out of the 10 fake EOS attack events are related to server issues, e.g., attack in [26]. For rollback, 11 out of the 21 attack events are due to the wrong reveal strategy of server, the most famous one is detailed in [27]. Besides, 2 of them were the variant of rollback, which is related to the configuration of some nodes on EOS MainNet and detailed in [28]. At last, we excluded all the above contracts from our benchmark to make sure all the attacks are resulted from the code in the contract itself instead of the other factors.

The distribution of the benchmark is shown in Table II. Among the 52 smart contracts in the benchmark, EOSAFE flags 26 as vulnerable: these detection results include 0 cases of false positives and only one false negatives (all belongs to rollback), leading to precision and recall metrics of 100% and 96.97%, respectively. The precision, recall and F1-measure of each vulnerability detector are shown in Table II. It is worth noting that, for all the patched versions of vulnerable ones, we reported “safe” for all of them with no false positive. Additionally, for fake EOS, fake receipt, and missing permission check vulnerabilities, we identified all the vulnerable versions without missing.

We further investigate the failure case to understand the root causes. For the only false negative case of rollback, i.e., fairdogegame/betdogewallt, the root cause is the number of suspicious reveal is too many to build path and symbolic execute each of them within a given timeout (5 minutes here) according to the Algorithm 4. After reverse engineering and manually locating the vulnerable function, i.e., func73, we can get a correct result.

Therefore, the false negative is introduced by the optimization strategies, which is a trade-off between accuracy and scalability. It is easy to tune our approach to cover these exceptional cases, e.g., by exploring more paths and increasing the analyzing time. Nevertheless, these exceptional cases are rarely seen during our experiments, as most smart contracts are not too complicated to be handled by our engine.

2) Results: Among the 52 smart contracts in the benchmark, EOSAFE flags 26 as vulnerable: these detection results include 0 cases of false positives and only one false negatives (all belongs to rollback), leading to precision and recall metrics of 100% and 96.97%, respectively. The precision, recall and F1-measure of each vulnerability detector are shown in Table II. It is worth noting that, for all the patched versions of vulnerable ones, we reported “safe” for all of them with no false positive. Additionally, for fake EOS, fake receipt, and missing permission check vulnerabilities, we identified all the vulnerable versions without missing.

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B. RQ2: How many smart contracts are vulnerable?

The previous evaluation suggested the high accuracy of EOSAFE. Thus, we further apply EOSAFE to all the contracts, to measure the presence of vulnerabilities in the wild.

1) Dataset: We consider all the 53,666 smart contracts (including history versions) from the June 9, 2018 (the very beginning of EOS MainNet) to November 15, 2019, which are collected by our customized EOSIO client.

These 53,666 smart contracts belong to 5,574 accounts. Note that, different from Ethereum smart contracts that cannot be modified once deployed, EOSIO contracts could be updated and bind with the same account as explained in §II-B. Thus, we use the EOSIO account to label each unique smart contract, i.e., one account may correspond to multiple contract versions. As a result, we have 53,666 different versions of smart contracts, which belong to 5,574 EOSIO accounts.

As the rollback vulnerability is only related to the gambling DApps, we thus can shrink our candidate list here. We refer to DAppTotal [29] – a credible multi-platform DApp browser, to label the gambling DApps and use such contracts for rollback vulnerability detection. For the other three kinds of vulnerabilities, we apply our detectors to all the 53,666 smart contracts (see Table III).

| Vulnerability          | # Samples(Vul/Safe) | Precision | Recall | F1-measure |
|------------------------|---------------------|-----------|--------|------------|
| Fake EOS               | 14 (7/7)            | 100.00%   | 100.00%| 100.00%    |
| Fake Receipt           | 10 (5/5)            | 100.00%   | 100.00%| 100.00%    |
| Rollback               | 18 (9/9)            | 100.00%   | 88.39% | 94.12%     |
| Missing Permission Check | 10 (6/4)*          | 100.00%   | 100.00%| 100.00%    |
| Total                  | 52 (27/25)          | 100.00%   | 96.97% | 98.46%     |

* 4 pairs of the missing permission check samples are manually crafted.
TABLE III
VULNERABILITY DETECTION RESULTS IN THE WILD.

| Type               | # Contracts | # Vulnerable (%) | # Unique | # Vulnerable (%) |
|--------------------|-------------|------------------|----------|------------------|
| Fake EOS           | 53,666      | 1,457 (2.71%)    | 5,574    | 272 (4.88%)      |
| Fake Receipt       | 53,666      | 7,143 (13.31%)   | 5,574    | 2,192 (39.33%)   |
| Rollback           | 17,594      | 1,149 (6.61%)    | 913      | 84 (9.29%)       |
| Missing Permission | 53,666      | 8,373 (15.60%)   | 5,574    | 662 (11.88%)     |
| Check              |             |                  |          |                  |

Total: 53,666 13,752 (25.63%) 5,574 2,759 (49.50%)

TABLE IV
THE TIME TO FIX THE VULNERABILITIES.

| Type               | # Unique (Vul) | # Latest with Vul (%) | # Patched (%) | Patch Time |
|--------------------|----------------|-----------------------|---------------|------------|
| Fake EOS           | 212            | 207 (76.10%)          | 65 (29.80%)   | 14.85d     |
| Fake Receipt       | 2,192          | 1,755 (79.85%)        | 457 (20.85%)  | 24.01d     |
| Rollback           | 84             | 28 (33.33%)           | 56 (66.67%)   | 4.24d      |
| Missing Permission | 662            | 313 (47.28%)          | 349 (53.72%)  | 4.38d*     |
| Check              |                |                       |               |            |

Total: 2,759 2,080 (75.29%) 679 (24.81%) 16.84d

*The average patch time for missing permission check is calculated on the action level.

2) Overall Results.: Table III shows the overall results. Surprisingly, over 25% of the 53,666 smart contracts (including historical versions) are vulnerable (see Column 3). The missing permission check vulnerability is the most prevalent vulnerability, affecting over 15% of the smart contracts. The fake receipt vulnerability is also quite common, with over 10% of the smart contracts suffering from it. For the rollback vulnerability, although we only analyzed 17K smart contracts of gambling DApps, over 1,000 of them are vulnerable. The fake EOS vulnerability affects roughly 2.7% of the smart contracts. It suggests that security vulnerability is prevalent in the EOSIO smart contract ecosystem, and reveals the urgency to identify and prevent such vulnerabilities.

Vulnerable Unique Smart Contracts. As one smart contract may correspond to multiple versions, thus we further characterize the distribution of vulnerabilities from the perspective of unique contracts (accounts). As shown in Column 5 of Table III for the 5,574 unique contracts, roughly half of them have at least one vulnerable version. 10% of unique smart contracts account for 61.24% of vulnerable versions, which indicates most of vulnerable versions are imported by a small portion of smart contracts. Besides, there are 1,793 unique smart contracts, whose versions are all vulnerable (41% of them have at least two versions). The contract eos- sanguone, which is a popular game DApp, has the most number of vulnerable versions (356 versions). By manually inspecting, we found that all its versions released before September 4, 2019, have suffered from the fake receipt vulnerability, and then the vulnerability was patched by the developer. The missing permission check vulnerability has been found since August, 2019, which may due to the importance of the new function without authority check.

3) Time to fix the vulnerability.: As we have analyzed the evolution of vulnerabilities across different versions, it is thus necessary to further investigate the time to fix the vulnerabilities for each unique smart contract, which could be used to measure the window period for the attackers to exploit these vulnerabilities.

Result. As shown in Table IV for the 2,759 unique smart contracts with vulnerable versions, over 75% of them still have at least one security vulnerability in their latest version by the time of our study. 679 unique smart contracts have patched all their vulnerability during their evolution, and the average time of window period is 16.84 days.

Patch Rate. We further analyze the patch rate across vulnerabilities. The rollback vulnerability has the highest patch rate (over 66%), and the average window period is roughly 4 days. The reason for timely response might be that the rollback vulnerability only exists in game/gambling DApps, which usually have high balance in their accounts. The loss could be devastating if developers leave the vulnerability alone. For the missing permission check, 349 smart contracts have patched all their missing check actions. Note that, we measured the average patch time on the action level here, as one vulnerable contract may have more than one missing permission check action. There are 647 patched actions in total – roughly 500 of them are patched within only one day, while the overall patch time is 4.38 days. It suggests that most of the missing permission checking actions are patched timely, while a few contracts take relative long time to fix them. In contrast, the fake EOS and the fake receipt vulnerabilities have the lowest patch rates (i.e., roughly 20%), and the patching time is relative long (i.e., 2 to 3 weeks on average). Our manually checking found that, half of the smart contracts related to fake receipt are patched within 24 hours, which further indicates some inactive smart contracts drag the average patch time. We manually examined all the inactive smart contracts (accounts), and found most of them have no balance and very few transactions, which are usually not the targets of attackers.

RQ-2 Answer

Security vulnerabilities are widespread in the EOSIO smart contract ecosystem. Over a quarter of the smart contracts and roughly half of the unique accounts have been exposed to the threats introduced by the vulnerabilities. Worryingly, a large portion of the vulnerabilities have not been patched timely, leading to long window periods for attackers.

C. RQ3: How many smart contracts have been exploited?

Our previous exploration suggests that a large portion of the smart contracts in the EOSIO ecosystem are vulnerable, and developers take a relative long time to fix the vulnerabilities in general, which posing great security threats. Thus, we further seek to explore how many of the vulnerable smart contracts have been successfully exploited by the attackers in the wild.

1) Approach.: It is not trivial to identify the security attacks of EOSIO. Until recently, a lot of ad hoc (often manual) efforts of security researchers [24, 25] are necessary to verify those attacks. Thus, given the vulnerable smart contracts, we first collect all their related on-chain transactions, and then design a set of heuristics to pinpoint the suspicious attacks, which
will be used to facilitate the further manually verification to determine the real attacks.

We have collected over 2.5 billion transactions records (ranging from June, 2018 to November, 2019) in total, which are then used to identify attacks as follows.

**Fake EOS Attack.** The most important behavior of this attack is to defraud the true EOS tokens from the vulnerable smart contract by using the fake EOS tokens, which can be identified through the transaction records storing the information of token issuers.

According to the observation, we will first filter out all the transactions of token transfer whose token symbols are “EOS” group by date. Then, these transactions will be grouped on the basis of the following definitions:

- **fake-sending** transactions that send fake EOS tokens.
- **true-sending** transactions that send true EOS tokens.
- **true-receiving** transactions that receive true EOS tokens.

As a result, we can define a **potential** attack as a sequence of a fake-sending transaction followed by a true-receiving transaction. Note that, a fake-sending transaction A can be joined with a true-receiving transaction B, if and only if they appear on the same day while A occurs before B. For all these potential transactions, we focus mainly on those who have gained more true EOS tokens than they spent. To this end, we will further examine the input-output ratio between the attacker and the vulnerable contracts to determine the suspicious attacks.

Finally, based on the suspicious attacks, we will verify whether the vulnerable smart contract will resume the normal execution (e.g., running a lottery for a real player) after receiving the fake EOS tokens. If so, we will mark the suspicious transaction as a fake EOS attack.

**Fake Receipt Attack.** The key feature of this attack is that the vulnerable smart contract is misled by the fake notification to receive tokens, while the actual token transfer occurs between the two accounts belonging to the same attacker (see §III-B). For simplicity, we will use from_account and to_account to represent the two accounts in the following, where to_account will send the fake receipt to vulnerable contract, and from_account is the ultimate beneficiary.

Accordingly, we will first query all the transactions of token transfer whose tokens are issued by eosio.token and token symbols are “EOS”, to get all the true EOS token transfers. Then, we will filter out the transactions whose receivers are neither eosio.token, nor the from_account or to_account. These transactions will be regarded as the fake receipts with crafted notifications. Next, if a from_account sends a fake receipt before making profits from the vulnerable contract, we will mark the corresponding transaction as potential. After that, by eliminating the unrelated EOS spending transactions (e.g., for testing purpose initiated by the attacker), we focus mainly on those who have gained more true EOS tokens than they spent. If the input-output ratio are still high, the corresponding transactions are labeled as suspicious.

Finally, we will manually check the suspicious transactions whether the vulnerable smart contract will resume the normal execution after receiving the fake receipts. If so, we will mark such a transaction as a fake receipt attack.

**Rollback Attack.** As mentioned in §III-C, the transaction of this attack is composed of sequential invocations of actions, which can be used as the pattern to identify the attack.

Specifically, we will first filter out all the transactions who contains at least four actions as the potential transactions. Next, we will select suspicious transactions which as long as meet the following four conditions: (1) the first and the last actions must be invoked in the same contract, where the first means to start the attack, and the last will determine whether the rollback is necessary after receiving the reward from the vulnerable smart contract. (2) the two actions in the middle must be token transfers through eosio.token, and the sender and the receiver (either one must be the vulnerable smart contract) of the two actions are arranged opposite to each other. (3) at least one of the counterparties, i.e., either the sender or the receiver, is labeled as the gambling or game DApp. (4) the amount of tokens transferred from the vulnerable smart contract is more than it received. Besides, it is worth noting that, the rollbacked transactions will not be recorded on the chain. As a result, we have to manually check the player’s successful rate per unit time, namely, if it is oddly high than the others, we will mark the suspicious transaction as a rollback attack.

**Missing Permission Check Attack.** Because authority information is along with the invoked transaction, we can examine whether it belongs to the callee contract to identify this attack. More precisely, we will first screen out all the transactions whose target actions are the vulnerable actions, to get suspicious transactions. Then, if the transaction’s authority does not belong to that smart contract the action belongs to, we will mark it as a missing permission check attack.

2) Results.: The overall result is shown in Table V. We have identified 48 attacks in total, including 9 fake EOS attacks, 27 fake receipt attacks, and 12 rollback attacks. Additionally, we also identified 183 invoked actions (belonging to 144 contracts) which missed the permission check (see Table VII in Appendix). Note that, for these missing permission check actions, some of them are designed intentionally instead of unexpected implementation. It is hard to differentiate whether they are attacks or not, and it is impossible to estimate the financial loss. Therefore, we regard them as misuse actions instead of attacks.

| Type                | # Attacks | # Attacker / Victims | Financial Loss ($) | # Verified |
|---------------------|-----------|----------------------|--------------------|------------|
| Fake EOS            | 9         | 10 / 9               | 652,428.48         | 8          |
| Fake Receipt        | 27        | 28 / 17              | 1,020,831.94       | 5          |
| Rollback            | 12        | 12 / 9               | 52,984.00          | 12         |
| Missing Permission  | 183       | - / 144              | -                  | -          |
| Check               |           |                      |                    |            |
| **Total**           | **48**    | **50 / 34**          | **1,726,244.42**   | **25**     |

* Exclude the results of missing permission check.
TABLE VI

| Attack Type | Attacker Account(s) | Victim Account | EOS Loss | Amount Loss ($) |
|-------------|---------------------|----------------|----------|-----------------|
| Fake Receipt | alt^{**}23, wh^{**}71 | eosbeltrn1   | 138,319.80 | 756,609.30 |
| Fake EOS    | re^{**}et         | ecosstabig87 | 63,014.10  | 327,673.32 |
| Fake Receipt | re^{**}et, eq^{**}91 | skiapimenilac | 144,341.71 | 264,019.99 |
| Fake EOS    | re^{**}et         | ecosbeltrn1   | 44,247.45  | 254,132.56 |
| Fake Receipt | be^{**}51, be^{**}502 | epsectacos | 17,358.73  | 41,559.07 |
| Rollback    | ey^{**}70c        | ecosgymus44  | 14,903.19  | 37,257.97 |
| Fake EOS    | mpo^{**}rer       | ecosluckydice | 3,459.38   | 3,459.38 |
| Rollback    | yl^{**}fan        | mutagambling | 1,141.71   | 2,359.38 |
| Total       | -                  | -             | 241,437.30 | 1,638,903.89 |

Impact of Attacks. The 48 identified attacks lead to over 341K EOS loss, which is roughly 1.7M USD according to the close price of the date of attacks. Note that, we have collaborated with a leading blockchain security company to report these attacks to the DApp developers, and 27 of them have been confirmed, accounting for more than 99% of the total loss. All the unconfirmed suspicious attack events are small-scale (only relate to a few EOS), and most of these DApps are no longer active. The Top-10 confirmed attack events are listed in the Table [VI]

Unexploited Vulnerable Contracts. It is interesting to observe that, although thousands of contracts are vulnerable (see Table[III]), only a few of them have been successfully exploited by attackers. We manually sampled some smart contracts for reverse engineering and inspecting their transactions, we found there are mainly two reasons leading to this. First, the popular smart contracts (with high balance) are the main targets of attackers, but these vulnerable contracts can be patched in time, and leave a very short window period for attackers. Based on the transactions, we found that attackers are always trying to exploit the popular contracts, and some attacks are indeed succeed (see Table[VI]), while most of them were failed. Second, as we mentioned in [VII-B], most of the unpatched smart contracts are inactive ones that have low balance, which attract low attention of attackers, considering the trade-off between low profit and the cost of attacks.

RQ-3 Answer

EOSIO suffers from a number of serious attacks. Although only a few vulnerable smart contracts have been exploited, most of them are popular ones, which caused great financial loss (over 1.7 million USD). It is urgent for DApp developers to identify and patch vulnerabilities timely.

VIII. THREATS TO VALIDITY

First, our system inherits the limitation of symbolic execution, i.e., path explosion. Although we have implemented several optimization strategies to address the issues, EOSAFE still produces some false negatives, as we discussed in [VII-A]. However, we believe that this is not a big issue for our system. On the one hand, most of the smart contracts are not as complicate as other software (e.g., mobile apps). Our evaluation suggests that a large portion of smart contracts can be fully analyzed in a short time. On the other hand, we have proposed specific optimization methods when searching for the four kinds of vulnerabilities, which could eliminate most irrelevant paths. Nevertheless, we agree that we can take advantage of advanced symbolic execution techniques (e.g., search heuristics [30, 32], path merging [33, 35]) to alleviate path explosion.

Second, we rely on heuristics and semi-automated methods to verify attacks (see [VII-C]). This, of course, might not be scalable and could mean that we only offer a lower-bound of attacks. However, a large portion of the attacks we identified are confirmed by DApp teams, which suggests that our approach is quite reliable. Nevertheless, we agree that some techniques (e.g., dynamic testing) can be applied to help us automatically identify attacks. In this paper, our main contribution is automatically detecting the security vulnerabilities, while attack verification is not a main focus in this work.

Third, security vulnerabilities were reported from time to time. It might be that some new vulnerabilities we did not cover in this current prototype, as well as the general vulnerabilities in other software systems, such buffer overflow. In this paper, we focus only on the EOSIO-specific vulnerabilities, the main reason is that we are lacking ground-truth of other security bugs. Nevertheless, we argue that it is easy to extend our system to cover other vulnerabilities, as the symbolic execution engine and the scanner framework are generic. Moreover, EOSAFE can also work on Wasm bytecode of other platforms (e.g., web), while the only effort is to resolve the library dependency of the corresponding platform.

IX. RELATED WORK

WebAssembly Bytecode Analysis WebAssembly is the new low-level language for the web. There are only a handful work on analyzing the Wasm bytecode [36, 40]. For example, Lehmann et al. [38] has proposed a general-purpose dynamic analysis system for Wasm, which allows developers or researchers to implement heavyweight dynamic analysis, e.g., instruction counting and memory access tracing. Researchers also proposed dynamic taint analysis frameworks for Wasm [36, 37]. However, all of them were focused on web applications, and almost all of them were dynamic analysis. In this paper, we implemented a general symbolic execution framework for Wasm, and made effort to support the security analysis of EOSIO smart contracts.

EOSIO Analysis There are several works were focused on the EOSIO ecosystem [41, 45]. For example, Huang et al. [44] proposed a method to identify the bot-like accounts in EOSIO based on transaction analysis. Lee et al. [45] introduced and studied four attacks stemming from the unique design of EOSIO. Several technical blogs [7, 8, 26, 28, 46, 47] from the industry have reported the security attacks of EOSIO. However, there are no available work available on detecting the security vulnerabilities in EOSIO.

Vulnerability Detection of Ethereum Smart Contracts Ethereum has received lots of attention from academia, and
a number of studies were focused on the vulnerability detection [9][16], [48][51]. For example, [13], [50], [51] were mainly focused on the overflow problem in Ethereum smart contracts. Luu et al. [15] proposed Oyente, the first symbolic execution tool for detecting vulnerabilities in Ethereum smart contracts. Machine learning and fuzz testing techniques [48], [49] are also adopted to identify the vulnerabilities of Ethereum smart contracts. As we mentioned earlier, the two ecosystems (Ethereum and EOSIO) are totally different, and no previous work on Ethereum can be applied to analyze EOSIO smart contracts directly. Nevertheless, we admit that the general idea of Ethereum vulnerability detection can be used to improve our work.

X. CONCLUSION

To the best of our knowledge, this paper presents the first work on detecting security vulnerabilities in EOSIO smart contracts. We propose EOSAFE, an accurate and scalable framework, which is capable of detecting four kinds of EOSIO specific vulnerabilities. Experiment results suggest the promising performance of EOSAFE. Our large-scale measurement study further reveals several serious issues in the ecosystem, i.e., over 25% of the smart contracts are vulnerable and a number of high-profile attacks have been successfully carried out. Our framework can be easy extended to cover additional vulnerabilities, and to analyze the Wasm bytecode of other platforms (e.g., web applications) as well.
XI. APPENDIX

A. Detector’s Algorithms

The detection algorithms for the 4 kinds of vulnerabilities are shown in Algorithm 2-5, respectively.

Algorithm 2 Fake EOS Detector.

Description: It implements the interface LocateFuncs

1: procedure LOCATEFUNCS(instructions)
2: Init(targetFuncs)
3: apply ← ExtractApply(instructions)
4: Update(targetFuncs, (apply, “apply”))
5: return targetFuncs

Algorithm 4 Rollback Detector.

Description: It implements the interface LocateFuncs

1: procedure LOCATEFUNCS(instructions)
2: Init(targetFuncs)
3: revealFuncs ← ExtractReveals(instructions)
4: Update(targetFuncs, (revealFuncs, “reveal”))
5: return targetFuncs

Algorithm 5 Missing Permission Check Detector.

Description: It implements the interface LocateFuncs

1: procedure LOCATEFUNCS(instructions)
2: Init(targetFuncs)
3: apply ← ExtractApply(instructions)
4: Update(targetFuncs, (apply, “apply”))
5: return targetFuncs

B. A list of Identified Missing Permission Check Actions.

We have identified 183 missing permission check actions, as shown in Table VII

Algorithm 3 Fake Receipt Detector.

Description: It implements the interface LocateFuncs, susTsfs - all suspect transfer functions, susTsf - suspect transfer

1: procedure LOCATEFUNCS(instructions)
2: Init(targetFuncs)
3: susTsfs ← ExtractTransfers(instructions)
4: for all susTsfs from susTsfs do
5: Update(targetFuncs, (susTsfs, “transfer”))
6: apply ← ExtractApply(instructions)
7: Update(targetFuncs, (apply, “apply”))
8: return targetFuncs

Description: It implements the interface ExecDetector

1: procedure EXECDETECTOR(cfg, pathTree, label)
2: constraints, _ ← ExtractFrom(pathTree)
3: vul ← False
4: for all c from constraints do
5: transfer ← IsTransfer(c)
6: codeCheck ← CodeChecked(c)
7: if transfer ∧ ¬codeCheck then
8: cond ← PathToTransfer()
9: if cond ∧ ValuableTransfer(c) then
10: vul ← True
11: return vul

Description: It implements the interface ExecDetector

1: procedure EXECDETECTOR(cfg, pathTree, label)
2: constraints, _ ← ExtractFrom(pathTree)
3: vul ← False
4: Init(pairs)
5: for all c from constraints do
6: action ← HasAction(c)
7: codeIsReceiver ← CodeReceiver(c)
8: if action ∧ codeIsReceiver then
9: suspendFunc ← ExtractFunc(c)
10: Update(pairs, (suspendFunc, action))
11: for all (suspendFunc, action) from pairs do
12: isValuable ← FindPath(cfg, suspendFunc)
13: authChecked ← FindPath(cfg, suspendFunc)
14: if isValuable ∧ ¬authChecked then
15: vul ← True
16: return vul
| Account | Action                          | Account | Action                          | Account | Action                          |
|---------|---------------------------------|---------|---------------------------------|---------|---------------------------------|
| 214odicedice | leave                            | eosknightsio | rebirth3                        | oneplayslots | clearrow                       |
| akdexiononce | clear                            | eosknightsio | skcell                          | oeyeyeeyeo | idex                           |
| akdexiononce | nonce                            | eosknightsio | signup                          | oeyeyeeyeo | iban                           |
| alibabaapo11 | jackpot                          | eosknightsio | skillreset                      | paritysupply | adduser                       |
| apensordata | update                           | eosknightsio | petgacha3                       | paritysupply | newaccount                    |
| arbarotokenn | create                           | eosknightsio | itemvup3                        | paritysupply | stake                          |
| arbarotokenn | claim                            | eosknightsio | rebirth                         | pariseed123 | refund                         |
| baccarat.e | reveal                           | eoslotteryes | login                          | pscoreptrcl | refreshkey2                   |
| bairenniusu | reveal                           | eospayserver | login                          | pscoreptrcl | refreshkey                    |
| bancor3code | jackpot                          | eospredictio | reqpredict                      | pickownbonus | withdrawn                    |
| battlebricks | startattend                      | eostamption | trigger                        | pickowngames | withdrawn                     |
| betmoonadmin | makebet                          | eosangouone | operateboss                     | pingwallet | m                              |
| bingotbegame | playlucky                        | eoswinnerdic | initcontract                   | putvux3byuce | clear                         |
| bingotbegame | playbonuslot                     | eoxystoken22 | un stake                        | pqtpiqelogy | m                              |
| blackjack.e | resolve                          | eoxystoken22 | getshare                        | pythonogol | update                         |
| blocklisten | adrequest                        | eparticlectr | brainclmid                      | rbagecoins | login                          |
| bluebetthree | login                            | eparticlectr | ffnlyhash                       | rbagecoins | logingame                      |
| bluebetthree | firstlogin                       | eparticlectr | oldvoteupurge                   | rating.pr | check                          |
| bosbtc.io | r Munablerb                      | eparticlectr | finalize                        | resetscontrac | childreflect                  |
| bosbtc.io | rollback                         | eparticlectr | rewardclmid                     | romangame222 | loginvestor                   |
| bosbtcchain | r Ministrucin                   | eparticlectr | proreward                        | roniletle | reveal                         |
| candy.w | manureward                       | exchangechanger | accomplish                   | sanlijishubu | sign                          |
| casinoorlando | withdraw                        | fairtkuai3kkk | close                           | segspzuutce | rand                           |
| conquerworld | end                               | farmeosrich1 | endprofit                       | scratchcards | scratch                       |
| cheroestest | battle                           | farmeosrich1 | profit                          | scratchers55 | reveal                       |
| cryptsangoku | clear                            | farmeosrichx | profit                          | signupscom | clearexpired                   |
| daccustodia1 | newperiod                        | farmeosrichx | endprofit                       | slotcontract | initstat                      |
| dappbaccarat | reveal                           | farmeosrichx | endprofit                       | slotcontract | initstat                      |
| dappbaccarat | reveal                           | findexindex | execute trade                   | slotmachine1 | reveal                       |
| dappshield | addseckonfig                      | g4ydgmyhege | deleterow                       | stakemine123 | refresh                       |
| deltadexcode | preparetrade                     | g4zkqobqhefe | deleterow                       | string.x | startgame                      |
| dgatopoker | reset                             | gambitprofit | un stake                        | superarmy123 | upuduser                       |
| dgatopoker | reselladder                       | gamesykpools | release                         | testblueuser | upudater                       |
| dgatokr | stake                            | godice.e | reveal                           | thebetxowner | printresults                  |
| diceater5a | verifier                          | gopokerdoto | verifycards                     | thedeo games | stake                         |
| dollarbilgo | check                             | gyrtetokenen | generate                        | thedepositgw | mint                           |
| dsdaevaefat | claim                             | helloworldp | out                              | therealkarma | refund                         |
| deltacell123 | resolve                          | horustokenio | claim reward                    | tothemoment | childing                      |
| dlbaochain1 | deleteroom                       | horustokenio | refund byid                     | trustbankchat | reveal                       |
| eeg.io | resetcode                         | horustokenio | refundhorus                     | trybenetwork | addtesser                     |
| elpaymentcom | claim                           | iloveq | go                               | ttblackjack | dg                             |
| enverns. | bank                               | jmihongbao11 | rcv                              | ultrahikkash | withdraw                       |
| eoslibchange | ugo                              | kdsrgkdrspg | fabi                            | undevitool1 | deleteysys                     |
| eosbankamea | prepare                          | koit111111 | btd                            | untoretsterv1 | deletemail                    |
| eosbankfund | prepare                          | km4io | un stake                        | uusercontract | buy                           |
| eosbaoserver | jackpot                          | kuaio | stake                           | virtualusers | checksign                     |
| eoscubetoken | signup                            | lumeospolis | uppollikes                      | wangshaoyong | setcf                         |
| eosdaqonswap | erasingcon propose               | lumeospolis | upcmnblogs                      | wardstar.e | reveal                         |
| eosdlongjohn | gen                               | lametokencre | lock                           | wealthplan33 | fuverifier                     |
| eosdcontract | positionadd                       | lametokencre | unlock                          | weoservices | destroytoken                  |
| eosdorclize | refreshutil                      | lynxeoschain2 | cleardb                        | whaleexgate4 | execute                       |
| eosesvenstate | sticking                        | lynxeoschain3 | setupkey                        | whaleexhelpu | un stake                       |
| eosevenstate | claim                            | lynxeoschain3 | cleardb                        | whaleexhelpu | stake                         |
| eostakerbatl | init                             | lynxeosgame4 | cleardb                        | wizardlights | cleanwizd                     |
| eosgamesprod | pong                             | marvellous3d | reveal                          | wizardmarket | createsale                    |
| eosshadowsha | jackpot                           | mhnntestcont | addtename                       | wizardtoken | createwizard                  |
| eosjackpool | claim                             | monstereosio | feedpet                         | worldconques | end                           |
| eoskeydice11 | initcontract                      | mymillionsio | collectone                      | xiongzhend13 | replacebet                    |
| eosknighthsio | skwear                           | mymillionsio | collectall                      | xmassnowball | updatecamp                    |
| eosknighthsio | skself                           | mymillionsio | collectall                      | xmasnowball | updatecamp                    |
| eosknighthsio | itemvup                           | mypaybankcap | updateclaim                    | xpietcore11 | ping                          |
| eosknighthsio | petgacha                          | mypaybankcap | claim                           | yizeshenzhen | erasingcon                    |
| eosknighthsio | petgacha                          | oneplaygames | clearrow                        | yumsactivity | hit                           |