

SAMBA: Detecting SSL/TLS API Misuses in IoT Binary Applications

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Abstract—IoT devices are increasingly adopting Secure Socket Layer (SSL) and Transport Layer Security (TLS) protocols. However, the misuse of SSL/TLS libraries still threatens the communication. Existing tools fsou446(ors)5DetectilsSSL/TLSAlsMisusm-

used to successfully analyze 115 binaries and reports all of those binaries are subject to at least one SSL/TLS misuse. QEMU is also used to validate the detected vulnerabilities of IoT firmware. SAMBA can be extended to other SSL/TLS implementations and new types of SSL/TLS misuse through our generic signature construction mechanism.

Responsible disclosure: We have reported all confirmed findings to relevant parties.

II. BACKGROUND

This section introduces the SSL/TLS protocol and two types of vulnerabilities due to SSL/TLS API misuses.

A. SSL/TLS Overview

The SSL/TLS protocol is designed to provide secure end-to-end communication and is widely used in applications and protocols such as HTTPS [14] and SMTPS [15]. Establishing an SSL/TLS connection between two parties involves multiple rounds of interactions. To simplify the use of SSL/TLS, core functionalities of the protocol are encapsulated by various third-party libraries, such as OpenSSL [12] and GnuTLS [13]. With the help of SSL/TLS libraries, developers can easily establish SSL/TLS connections in their applications.

Fig. 1 gives an example of how to establish a secure SSL/TLS connection with the OpenSSL library. Firstly, the client configures the supported SSL/TLS protocol as TLS 1.2 (a secure version) by using `TLSv1_2_client_method()`. Next, a socket is set up for the SSL/TLS connection and the SSL/TLS handshake process is conducted by calling `socket()`, `SSL_set_fd()`, and `SSL_connect()`. To establish a secure SSL/TLS connection, it is important for the client to check the authenticity of the SSL/TLS server. To this end, the client should request the server certificate with `SSL_get_peer_certificate()`. If the certificate is sent by the server, its return value should not be `NULL` and `SSL_get_verify_result()` should be used to verify the server certificate. The verification result of `SSL_get_verify_result()` is stored in the `RAX` register. If the result is 0, i.e., `X509_V_OK`, it indicates that the server certificate has passed the verification. In this case, a secure SSL/TLS connection has been established between the client and the server. Otherwise, the SSL/TLS connection is shut down as the certificate verification fails.

B. SSL/TLS API Misuse

Given the inherent complexity of the SSL/TLS protocol, diversity of SSL/TLS library implementations and inadequate documentation of some libraries, developers may inadvertently misuse the APIs, resulting in severe security risks in real-world applications [1], [2]. The most common vulnerabilities caused by SSL/TLS API misuses are support of deprecated protocols and insecure certificate verification.

Deprecated Protocol Support (DPS). As shown in Fig. 1, the first thing for a client to establish an SSL/TLS connection is to send a hello message that specifies the supported

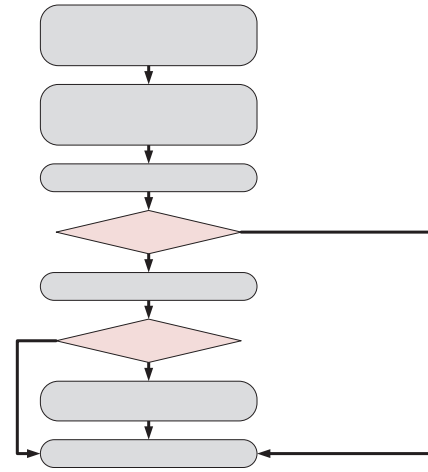


Fig. 1. Example OpenSSL API Usage.

SSL/TLS protocols. Existing research [3], [16] and RFC documents [17], [18], [19] have found certain SSL/TLS protocols susceptible to design flaws and should not be used. For example, if a client uses `SSLv3_client_method()` instead of `TLSv1_2_client_method()` to configure the support for SSL 3.0, the connection may be vulnerable to the POODLE attack [3]. To ensure a secure SSL/TLS connection, the client should avoid supporting deprecated/insecure protocols, i.e., SSL 2.0/3.0 and TLS 1.0/1.1.

Insecure Certificate Verification (ICV). During the establishment of an SSL/TLS connection, the client relies on the server certificate to ensure the authenticity and trustworthiness of the server. To this end, the client should request the certificate from the server at the handshake stage and then perform a series of checks to verify the validity of the server certificate. Otherwise, the connection is vulnerable to the MITM attack. An example of such vulnerability is that the result of `SSL_get_verify_result()` in Fig. 1 is properly examined.

III. SSL/TLS API MISUSES AND CHALLENGES

In this section, we first introduce two types of SSL/TLS API misuse. Then we present the technical difficulties associated with detecting SSL/TLS API misuses. Finally, we present the overview of our detection system—SAMBA.

A. Misuse Types

By analyzing documents of OpenSSL [12] and GnuTLS [13], the following two types of SSL/TLS API misuse are the API call sequence misuse (T-I) and the API data misuse (T-II), which may lead to incorrect certificate verification (ICV) and/or deprecated SSL/TLS protocol support (DPS). It can be observed that both types of misuse occur during the establishment of an SSL/TLS API connection.

1) *T-I: API Call Sequence Misuse:* This type of misuse occurs when a developer fails to invoke necessary APIs or invokes old APIs. For example, Fig. 1 shows a correct certificate verification API use. If a developer does not call `SSL_get_verify_result()`, the SSL/TLS connection

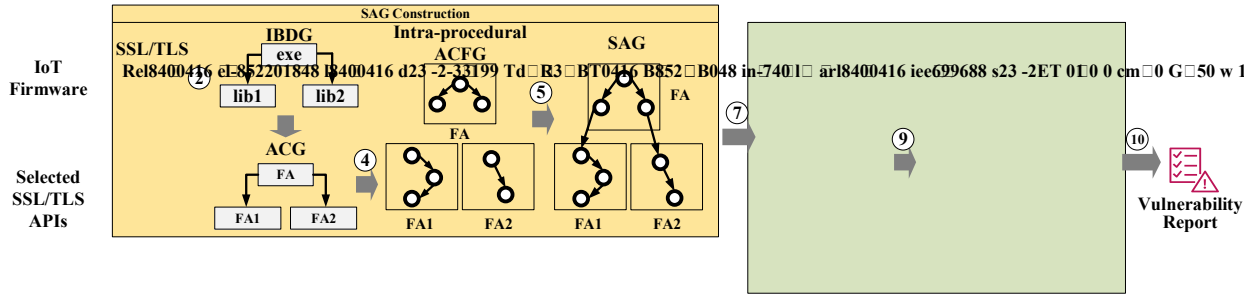


Fig. 2. System Overview

can still be established without verifying the server certificate, leading to the ICV vulnerability, which can be exploited by the MITM attack.

2) *T-II: API Data Misuse.*: Even if the API call sequence is correct, the misuse of data in the API calls in the sequence may still affect the security of the SSL/TLS connections. The API data misuse can be further classified into two sub-types: API argument misuse and API execution result misuse.

T-II.a: API Argument Misuse. Passing incorrect arguments to some SSL/TLS library APIs can result in insecure connections. For example, in an OpenSSL-based SSL/TLS client application, if the macro value `SSL_VERIFY_NONE` passed to the “mode” parameter of `SSL_CTX_set_verify(., int mode, .)`, the SSL/TLS connection can be established regardless of the server certificate verification result, causing the ICV vulnerability.

T-II.b: API Execution Result Misuse. It is crucial to check the execution results of certain SSL/TLS APIs. Otherwise, it can lead to the ICV vulnerability. These function execution results may be returned via a return value or pointer argument. As shown in Fig. 1, an OpenSSL-based SSL/TLS application uses `SSL_get_peer_certificate(.)` and `SSL_get_verify_result(.)` to request and verify the server certificate. The certificate verification result is stored in the return value of `SSL_get_verify_result(.)`. If the execution result is not correctly verified the established connection can be vulnerable.

B. Challenges

The main challenges in detecting misuses of SSL/TLS APIs in IoT are listed as follows.

(C-I) Path-explosion: In analysis of API usage in an IoT binary, extracting the SSL/TLS API call sequences is daunted by the path-explosion problem due to the complexity of the inter-procedure control flow graph (ICFG) of the binary. We find the SSL/TLS library APIs can be called in another library, and the executable indirectly calls the SSL/TLS APIs. In this case, the SSL/TLS API usage cannot be discovered by only analyzing the executable. The inter-binary analysis should be conducted and this makes the path-explosion problem worse.

(C-II) Diversity of SSL/TLS implementations: To facilitate the implementation of SSL/TLS in programming, a wide range of open-source SSL/TLS libraries have been developed, such as OpenSSL and GnuTLS. An SSL/TLS library may also consist of multiple versions. Within various SSL/TLS libraries

and versions, there exists a wide variety of SSL/TLS API misuse patterns. Expressing these patterns in a general way presents a significant challenge.

IV. SYSTEM DESIGN

In this section, we first present an overview of SAMBA and then present the details of the workflow of SAMBA.

A. Overview

Fig. 2 illustrates the workflow of SAMBA. The inputs are the *IoT firmware* and *SSL/TLS APIs of interest*. In Step ① in Fig. 2, binwalk [20] can be used to extract files from the IoT firmware, which contains executables, libraries, and other files. The executables and libraries are in the binary format. We are only interested in the executable that establishes SSL/TLS connections and its dependent libraries. SSL/TLS APIs of interest refer to those SSL/TLS APIs that are used to establish an SSL/TLS connection and transfer data with the SSL/TLS server. Those APIs are related with the two misuses introduced in Sec. III-A and will be used to tackle the path explosion problem. SAMBA outputs the vulnerability report generated by our static analysis, including SAG construction, misuse signature representation and API misuse detection.

SAG construction: By analyzing the ELF header of the executable, we can tell if the executable directly calls the APIs of the SSL/TLS library or it calls wrapper functions in other libraries. In the former case, we analyze the executable to discover misuses. In the latter case, we construct an inter-binary dependency graph (IBDG) in Step ② to discover the invocation relationship between the executable and its dependent libraries that call SSL/TLS APIs for further function-level analysis. The IBDG does not contain libraries that do not call SSL/TLS APIs or their wrapper functions. The former case can be viewed as a special latter case in which the IBDG contains only the executable as a node. Next, we use the SSL/TLS APIs of interest as leaf nodes to construct API call graphs (ACGs) backward for each binary in the IBDG in Step ③. Please note whenever disassembly of the binary is needed, we use IDAPython [21]. For each function in an ACG, we then create its control flow graph, but remove those control flows not related with SSL/TLS APIs so as to create SSL/TLS API-centric control flow graph (ACFG) in Step ④. Finally we obtain the SAG by merging these ACFGs based on API invocation relationship in Step ⑤.

Misuse signature representation: To detect the API misuse introduced in Sec. III-A, we propose a formal expression of

the SSL/TLS API misuse signatures based on SSL/TLS library documents and enumerate all SSL/TLS API misuse signatures in Step ⑥. These signatures are fed into the SSL/TLS API misuse detection in Fig. 2.

API misuse detection: We first extract the API call sequences from the SAG in Step ⑦ and map API call sequences to the misuse signature so as to detect the T-I—API call sequence misuses in Step ⑧. Data flow analysis is needed for specific SSL/TLS APIs to detect T-II—API data misuses. If an API call sequence uses such an API, we find the caller of the API and perform backward taint analysis and forward taint analysis on the CFG of the caller function in Step ⑨ and check if data is properly used so as to detect T-II misuses in Step ⑩.

B. SAG Construction

To solve the path explosion problem, we adopt a three-level reduction method to construct the SAG for further API misuse detection, including binary-level reduction, function-level reduction, and basic-block-level reduction.

1) **Binary-level Reduction in Step ②:** Since some libraries call the APIs of the SSL/TLS library and indirectly provide the capability of establishing SSL/TLS connections, we build the *inter-binary dependency graph* for the target executable and its dependent libraries to represent the dependencies among them. An IBDG is a directed graph in which the root node is the executable, and other nodes represent its dependent libraries. A directed edge in the IBDG means that the source binary depends on the destination binary, i.e., the source executable/library binary call the APIs of the destination library binary.

To create the IBDG, we recursively analyze the ELF header of the executable and its dependent libraries to derive the imported functions of the executable as well as the imported and exported functions of its libraries. By correlating the imported and exported functions, we can build a raw IBDG. We then prune nodes and edges not related with SSL/TLS APIs from the raw IBDG and derive the final IBDG so as to reduce the analysis space.

2) **Function-level Reduction in Step ③:** We construct the call graph (CG) for each binary in the IBDG and then leverage the SSL/TLS APIs of interest to prune nodes and edges corresponding to irrelevant functions on the CG so as to reduce the graph size at the function level and derive an API-centric call graph (ACG). If the executable directly calls the SSL/TLS APIs to establish the SSL/TLS connection, we only build an intra-binary ACG of the binary to extract the function call relationships among SSL/TLS APIs of interest and the functions that call these SSL/TLS APIs. If the SSL/TLS library is indirectly dependent by an executable binary, i.e., wrapped in other libraries, we first build intra-binary ACGs for the executable and all of its libraries in the IBDG. We can then derive an inter-binary ACG by merging these intra-binary ACGs based on the function calls.

Intra-binary ACG Construction. The construction of intra-binary ACG starts with constructing a CG of the target binary. We identify all used APIs of interest as leaf nodes of the ACG by scanning the functions in the CG. Next, starting

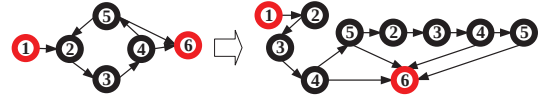


Fig. 3. Loop unrolling example

from these leaf nodes, we recursively perform backward traversal on the CG using the breadth-first search (BFS) algorithm to enumerate all parent nodes, i.e. caller functions, in order to construct the intra-binary ACG. Once we reach the root nodes (i.e., the functions that are not called by other functions), the intra-binary ACG is completely constructed. In this way, we eliminate all nodes not related with SSL/TLS APIs of interest from the original CG of the binary.

Inter-binary ACG Construction. Since circular dependencies (i.e., cycles) may exist within the IBDG and hinder the direct traversal of CGs of the binaries for inter-binary ACG construction, we discuss the ACG construction methods for the IBDG in the absence and presence of cycles respectively. In the case of an acyclic IBDG, the intra-binary ACG can be constructed backward and recursively based on the following rule: we build the intra-binary ACG for a binary only if all ACGs of its dependent libraries have already been constructed or if its successor is the SSL/TLS library. Once the intra-binary ACG is constructed and the binary is a library, we define the root nodes of the ACG (i.e., the export functions that call the the SSL/TLS APIs of interest) as the new APIs of interest. Next, we recursively traverse the IBDG backward to build the intra-binary ACGs based on the new APIs of interest until the ACG of the root node is constructed. In this way, we construct all the ACGs for the binaries in the IBDG.

We break the cycles in our context as follows. We first leverage the depth-first search (DFS) starting from the root node, i.e., the executable, of the IBDG to identify its cycle. We then take each node in the cycle as a root node to generate sub-IBDGs without other nodes in the cycle. The sub-IBDGs have two types: sub-graphs containing the SSL/TLS library and sub-graphs not containing the SSL/TLS library, in which the dependency relationship between the binaries in the IBDG and the SSL/TLS library is provided by the dependency relationship between other binaries in the cycle and the SSL/TLS library. For the sub-IBDGs containing the SSL/TLS library, we recursively build the ACG backward. After we construct the ACGs for all binaries on the first type of sub-IBDG, we can identify the APIs that are exports of the root node of the sub-IBDG and are related to the SSL/TLS API of interest, denoted as *propagation APIs*. We then find binaries in the original cycle that call the *propagation APIs* of

the inter-binary ACG for further basic-block-level analysis. It can be observed that during the ACG construction, we prune functions not related with SSL/TLS APIs of interest in the CGs of the binaries in the IBDG to reduce the graph size at the function level.

3) **Basic block-level Reduction in Step ④**: Since the ACG only illustrates the function level SSL/TLS dependency, we leverage the intra-procedural Control Flow Graph (CFG) of each function in the ACG to discover the SSL/TLS function call sequence. However, CFGs contain numerous basic blocks as nodes and control flow edges. This significantly increases the graph size and leads to path explosion. There may also exist loops in a CFG. The API-centric Control Flow Graph—ACFG—is derived by eliminating basic blocks not related with SSL/TLS APIs of interest and corresponding edges from a loop-free CFG and its size is reduced. Edges are added from the preceding blocks of a deleted basic block to the succeeding blocks of the deleted block.

We address loops in CFGs that introduce complexities in extracting API call sequences as follows. We first discover the loop and detect the back edge in the loop with the DFS algorithm from the root node of the CFG. For example, in Fig. 3, we perform the DFS from node 1, and discover a loop including nodes 2 to 5. The edge from node 5 to node 2 is a back edge. We create two copies of the loop. We then select one and delete its back edge. The back edge of the other loop copy is modified to point to the counterpart node in the previous loop as shown in Fig. 3 so as to construct a new loop-free graph and replace the original loop. Finally, based on the original loop, we establish edges between nodes in the loop-free graph, the entry and exit nodes, e.g., the edges from node 1 and the edges to node 6. In this way, we can construct the loop-free CFG. Unrolling the loop just once is sufficient, as further unrolling operations would result in the redundant calling of specific SSL/TLS API(s), and our document analysis indicates it does not adversely affect the security of SSL/TLS API usage.

4) **SAG Construction in Step ⑤**: We construct the final SAG by merging the previously constructed ACFGs. Specifically, we add edges from the nodes (i.e., basic blocks) within one ACFG that contain the instruction calling a function in the ACG to the root node in the corresponding ACFG of the called function.

C. Misuse Signature Representation

We present a formal expression of the SSL/TLS API misuse signatures and can enumerate all SSL/TLS API misuse signatures of different misuse types in various SSL/TLS implementations, addressing C-II. Fig. 4 shows the formal representation of the SSL/TLS API misuse signatures. A signature can consist of multiple Calls and Asserts that can establish an SSL/TLS connection. The Calls are SSL/TLS API calls. The args represent one or more arguments that can be passed to the APIs in the signature. The Asserts are data verification and the data can be divided into two kinds, i.e., the argument and the function execution result. The data is used in comparing with Integer, String, Boolean, and NULL in an expression.

```
Signature ::= Call+ | Assert+
Call ::= f(args) | ret = f(args)
args ::= arg | arg, args
Assert ::= assert(expr)
expr ::= arg comp operand | ret comp operand
operand ::= Integers | Strings | Boolean | NULL
comp ::= == | !=
f ::= target SSL/TLS APIs
```

Fig. 4. SSL/TLS API misuse signature formal expression

SSL/TLS API misuse signatures can be divided into three categories. The first category includes only T-I misuses, the second includes only T-II misuses, and the third includes both T-I and T-II misuses. For each API misuse signature, it may include the misuses leading to incorrect certificate verification, deprecated protocol support or both vulnerabilities. We have defined 23 signatures for T-I misuses, 18 signatures for T-II misuses, and 22 signatures for both T-I and T-II misuses for OpenSSL and GnuTLS. Because of the page limit, please refer to [22] for detailed signatures.

Fig. 5(a) shows an example of the third category of misuse signature used to discover a T-I misuse (API call sequence misuse). The upper block of Fig. 5(a) is the block of application code in question. The bottom block is the signature, which is used to detect the misuse in the block of application code. Specifically, `SSL_get_peer_certificate(.)` is called to request the server certificate, the `SSL_get_verify_result(.)` is not called to obtain the certificate verification result, and thus the server certificate is not correctly verified. This indicates a T-I misuse.

D. Misuse Detection

With defined misuse signatures in Sec. IV-C, we can perform misuse detection. We first extract SSL/TLS API call sequences from the constructed SAG by traversing the SAG forward from the root node. We filter out the sequences that do not include necessary APIs such as handshake and I/O APIs for SSL/TLS connection establishment and data transmission since the SSL/TLS connection cannot be actually established from (SSL/T010)99489 (obtMTJ/T1_1 9.9626 Tnd)-35381.94(SSL/T010)9

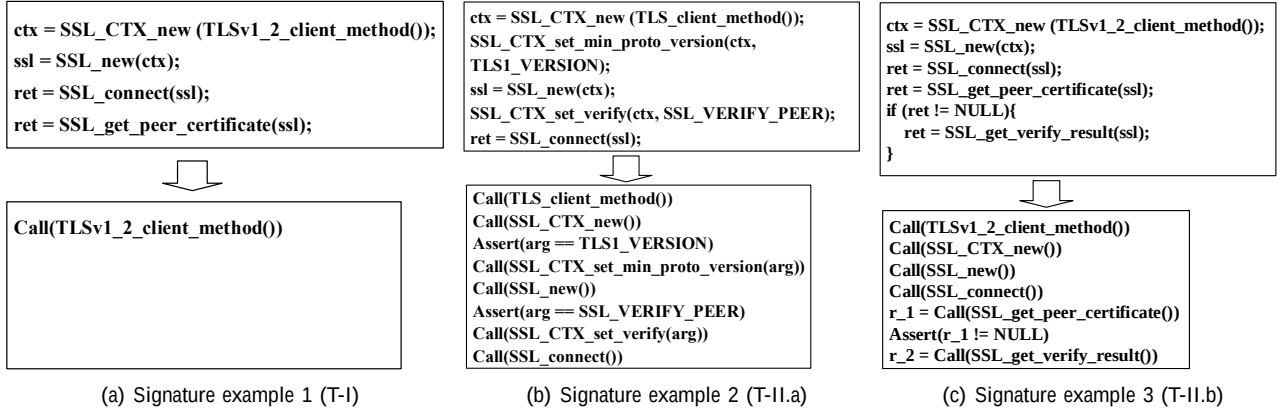


Fig. 5. SSL/TLS API misuse signature examples

identified APIs prone to argument misuse, and locate the instructions that call the APIs. Therefore, the register that stores the argument value is used as the taint source. In our context, the argument value passed to the APIs prone to argument misuse are either integer or string. We designate the assignment instructions (e.g., “mov” and “lea” in the x86 instruction set) in which the right-hand operand is an integer or a string address as taint sinks. Now we perform backward taint analysis to trace the taint propagation from the taint source to sinks. Since we trace backward, the taint information is propagated from the left-hand operand to the right-hand operand. The analysis stops when it encounters one of the taint sinks or reaches the first instruction in the CFG. If the taint source reaches the taint sink, we can determine that the right-hand operand of the sink instruction is the value passed to the parameter. By comparing the API call sequences and the identified argument value with each signature, we can detect if the target binary contains the T-II.a misuse.

For example, `SSL_CTX_set_min_proto_version(·, version)` can configure the minimum protocol support by the binary with the value passed to the “version” parameter. If a wrong value is passed, deprecated protocols can be supported. Therefore, if we discover this API in a call sequence, a backward taint analysis should be performed to find the argument value. If the API usage matches the T-II.a misuse signature in Fig. 5(b), we identify a T-II.a misuse.

To detect a T-II.b misuse, we first identify if SSL/TLS APIs prone to execution result misuse are called in the call sequences and then construct the intra-procedural CFGs for the caller functions of the identified APIs. In order to track the function execution result, we locate the register that stores the function execution result and use it as the taint source. We mark the compare instructions on the caller function’s CFG as taint sinks. We now proceed to forward trace the taint propagation. Specifically, the taint information is propagated from the right-hand operand to the left-hand operand. The analysis continues until it encounters a taint sink or reaches the last instruction of the CFG. If the taint source reaches one of the taint sinks, it indicates that the API execution result is verified and correctly used. Otherwise, if the taint source does not reach the taint sinks, it implies that the return

value is not adequately verified and misuse is detected. For example, in the upper code block in Fig. 5(c), the return value of `SSL_get_verify_result(·)` is not checked, and this matches the signature depicted. A T-II.b misuse is detected.

V. EVALUATION

In this section, we first introduce the experiment setup and evaluate the effectiveness of SAMBA. We then present the results of detecting vulnerabilities in real-world IoT binaries

TABLE I
GROUND-TRUTH EVALUATION RESULTS (RQ1)

		Ground Truth		Results							
		P	N	Suc	TP	FP	TN	FN	Coverage	Precision	Recall
ICV	SSLint	42	24	66	42	0	24	0	100%	100%	100%
	SAMBA	42	24	48	32	0	16	0	72.73%	100%	100%
DPS ¹	SSLint ²	50	7	-	-	-	-	-	-	-	-
	SAMBA	50	7	42	36	0	6	0	73.68%	100%	100%

¹ The SSL/TLS protocol supported in 9 SSL/TLS connections is determined during execution.

² Related work SSLINT does not discover the deprecated protocol support vulnerability.

(i) we locate all the SSL/TLS API usage that can establish SSL/TLS connections in the selected programs; (ii) we manually check each connection to identify if it is vulnerable to ICV (incorrect certificate verification) or DPS (deprecated protocol support) because of SSL/TLS API misuses. Since the manual examination of SSL/TLS usage is performed at the source code level, the correctness of the labeling can be guaranteed.

After about 45 man-hours of manual examination, we discover 66 SSL/TLS API sequences that establish SSL/TLS connections in these 30 programs as shown in Tab. I. For the certificate verification among the 66 connections, 24 connections have correctly verified the server certificate, while the other 42 have the certificate verification misuse issue. In terms of DPS, we find 50 connections support at least one deprecated SSL/TLS protocol and only 7 connections support secure SSL/TLS protocols. Note that we do not label the protocols supported in the other 9 connections because their supported protocols are determined during program execution, e.g., configured with command line argument.

Baseline. To the best of our knowledge, all existing SSL/TLS API misuse detectors rely on source code. We compare SAMBA with SSLINT

results are presented in Tab. II. Among the vulnerable 115 executables, 94 executables are vulnerable to ICV. 112 executables are found to be vulnerable to DPS. More specifically, there are 31 executables supporting SSL 2.0, 93 executables supporting SSL 3.0, 104 executables supporting TLS 1.0, and 55 executables supporting TLS 1.1. All these detected executables are vulnerable to MITM attacks or side-channel attacks, including POODLE [3] and Lucky 13 [26].

Analysis of Failures: For the 33 executables that SAMBA fails to analyze, we manually investigate these cases and find four causes. (i) SAMBA fails to obtain a complete call graph for 12 of them due to the limitations of IDAPython in fully extracting the call graph. SAMBA cannot discover all target APIs and extract correct API call sequences from a partial call graph. (ii) SAMBA does not find the invocation of read/write-related SSL/TLS APIs (e.g., `SSL_read` and `SSL_write`) in 8 executables. In this situation, it is impossible for SAMBA to extract a complete API call sequence for vulnerability signature matching. (iii) SAMBA crashes when analyzing 8 executables due to unknown bugs maybe in IDAPython. (iv) SAMBA encounters timeout errors for 5 executables.

Efficiency. To evaluate the efficiency of SAMBA, we measure its analysis time for all successfully analyzed IoT binaries. We find that the average time cost for SAMBA to analyze an executable is only 55.45 seconds, which is quite efficient. We further evaluate the contribution of the CFG pruning technique in improving the analysis efficiency of SAMBA. To this end, we implement a raw version of SAMBA which extracts API call sequences without CFG pruning and compare its performance with SAMBA. In the raw method, we first generate the inter-procedural CFG and then directly traverse all blocks to extract the SSL/TLS API call sequences. The results show that the raw version of SAMBA cannot extract the API call sequences of 67 executables within 8 hours. ra

the caller function of the SSL/TLS APIs. To address this issue, an inter-procedure data analysis is required and our system may generate inaccurate reports. However, while constructing our ground truth dataset, we notice that the argument value and the API execution result verification are closely associated with the SSL/TLS API prone to misuse. Thus, in our context, intra-procedure data flow analysis suffices.

B. Advantages of Binary-level Analysis

With the evolution of the SSL/TLS libraries, some APIs have been deprecated and replaced with new ones to support similar functionalities. However, for the consideration of compatibility, some deprecated APIs are renamed to the corresponding new APIs by preprocessor macros instead of directly removed. For example, the `SSLv23_client_method()` in OpenSSL is used to configure the client application to support SSL 2.0 and later protocols, and it has been deprecated after OpenSSL 1.1.0. If an application calls `SSLv23_client_method()` and is compiled with OpenSSL 1.1.0, the API call is replaced with `TLS_client_method()` instead. In this situation, the SSL/TLS protocols supported by the application are SSL3.0 and later protocols. Such practice illustrates the advantages of binary analysis in detecting SSL/TLS misuses. That is, the source code based methods [1], [2] will report more false positives than binary-level analysis tools due to the usage of preprocessor macros in SSL/TLS libraries.

VII. RELATED WORK

In this section, we present the most related work on API misuse vulnerability detection and static analysis based vulnerability detection methods.

A. API Misuse Vulnerability Detection

Third-party libraries play an important role in simplifying program development and the issue of API misuse attracts increasing attention [29], [30]. To address the API misuses, several detection methods [1], [2], [7], [31], [32] have been proposed. These methods can be divided into two categories: source-code-based misuse detection [1], [2], [31] and binary-code-based misuse detection [7], [32]. The source-code-based methods require access to source code of the target SSL/TLS application, and this limits their usage when the source code of the application and/or its dependent libraries is not available. The binary-code-based methods are more general since only binary files are required. Previous works focus on detecting cryptographic misuses [7], [32], mainly target the arguments passed to cryptographic APIs, and analyze if a specific API is used and if the argument passed to the API violates the correct usage rules. However, by analyzing documents of SSL/TLS libraries, we find the execution result of some APIs should be examined to verify the certificate authenticity. SAMBA can address the deficiencies of related work.

B. Vulnerability Detection with Static Analysis

Software analysis can be either static or dynamic analysis. In this paper, we focus on analyzing the IoT applications. Due to the diverse instruction sets and peripherals used in IoT devices, it is difficult to dynamically execute binaries even with an emulator such as QEMU. Therefore, we adopt static analysis methods to discover SSL/TLS API misuse vulnerabilities. There is related work using static analysis to discover IoT application vulnerabilities [33], [24], [34], [35]. For example, Shoshitaishvili et al. [33] present a system to automatically discover authentication bypass vulnerabilities in binaries based on backward slicing and symbolic execution. However, our work is the first to detect SSL/TLS API misuses in IoT firmware.

VIII. CONCLUSION

This paper introduces SAMBA, the first automatic tool designed to detect misuses of SSL/TLS APIs in IoT binaries. SAMBA utilizes a three-level reduction technique to construct an SAG for API call sequence extraction. Backward and forward taint analyses are then applied based on these sequences to understand the data flows of APIs prone to data misuse. By formulating API misuse signatures for OpenSSL and GnuTLS, SAMBA matches these signatures at the control and data flow levels to identify SSL/TLS API misuses in IoT binaries. Extensive experiments are conducted to validate SAMBA. We evaluate SAMBA with 30 Ubuntu SSL/TLS binaries, are able to analyze 73.21% of those binaries and achieve a precision of 100%. We also use SAMBA and successfully analyze 115 IoT binaries. We find 94 of the 115 IoT binaries are vulnerable to incorrect certificate verification, and 112 out of them support deprecated protocols. To validate the identified vulnerabilities, we emulate 37 IoT binaries with QEMU, and confirm the vulnerabilities are indeed present in these binaries. Particularly, we find vulnerabilities related to certificate verification in all the 37 binaries and 36 binaries support deprecated protocols. Our experiment results highlight the effectiveness and efficiency of SAMBA, shedding light on the insecure use of SSL/TLS APIs in today's IoT devices.

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