PATRIOT: Anti-Repackaging for IoT Firmware
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Abstract—IoT repackaging refers to an attack devoted to tampering with a legitimate firmware package by modifying its content (e.g., injecting some malicious code) and re-distributing it in the wild. In such a scenario, the firmware delivery and update processes play a central role in ensuring firmware integrity. Unfortunately, most of the existing solutions lack proper integrity verification, leaving firmware exposed to repackaging attacks, such as the one reported in [1]. If this is not the case, they still require an external trust anchor (e.g., a signing certificate), which could limit their adoption in resource-constrained environments.

To mitigate such a problem, in this paper, we introduce PATRIOT, a novel self-protecting scheme for IoT that allows the injection of integrity checks, called anti-tampering (AT) controls, directly into the firmware. The AT controls enable the runtime detection of repackaging attempts without the need for external trust anchors or computationally expensive systems. Also, we have implemented this scheme into PATRIOTIC, a prototype to automatically protect C/C++ IoT firmware. The evaluation phase of 33 real-world firmware samples demonstrated the feasibility of the proposed methodology and its robustness against practical repackaging attacks without altering the firmware behavior or severe performance issues.

Index Terms—IoT repackaging, Anti-repackaging techniques, IoT security, IoT firmware update, Firmware, IoT.

I. INTRODUCTION

The Internet of Things (IoT) paradigm enables the growth of low-cost embedded devices, provided with network connectivity and real-time capabilities, that are now used in many verticals, from logistics to precision farming and smart homes. Each IoT device is equipped with a firmware, i.e., a bundle that contains all the software needed to ensure the functioning of the device hardware. Typically, the firmware comprises a fully-fledged IoT operating system (like RIOT [2] or Contiki [3]) and at least an application that holds the core functionalities of the thing.

During the building phase, the device manufacturer equips the IoT device with a first version of the firmware. However, the functionalities required by an IoT device at deployment time are likely to change in the future. To this aim, the firmware will need frequent updates for a number of reasons: offer additional functionalities, support new communication protocols, and patch software bugs (including security vulnerabilities).

As the firmware has a central role in the life cycle of an IoT device, its security has raised serious concerns from the scientific and industrial community. To this aim, several works were proposed to evaluate the security of the firmware bundle (like [4] or [5]) and enforce the update mechanisms (e.g., [6] and [7]).

In particular, the integrity of the firmware delivered through an update process represents a major security threat, as witnessed by many real-life examples. For instance, the PsycoBot [8] was the first router botnet that altered the firmware of approximately 85,000 home routers and resulted in large-scale denial of service attacks. Also, the Zigbee Worm [9] was able to trigger a chain reaction of infections, initialised by a single compromised IoT device (light bulb), using a malicious firmware update image.

Attackers can retrieve the firmware in different ways, such as obtaining it from the vendor’s website, community forums, sniffing the OTA update mechanism, or dumping it directly from the device [10]. Once the original firmware is obtained, she can analyze it through reverse engineering techniques to extract sensitive information such as sensitive functions, encryption keys, hard-coded credentials, or sensitive URLs.

Thanks to such a knowledge, an attacker can craft a modified version of the firmware and try to re-distribute it in the wild, as if it was the original one [11].

This type of attack, called repackaging, is well-known in the mobile ecosystem, where attackers alter and re-distribute thousands of Android and iOS applications [12]. Unfortunately, such a security threat is barely considered in the IoT ecosystem, especially in low-end devices where the resource constraints limit the applicability of state-of-the-art mitigation techniques such as remote attestation or signature verification.

Furthermore, many of the existing solutions for low-end IoT devices focus only on some parts of the delivery process (e.g., from the update server to the device), or do not perform a proper verification of the downloaded firmware and hence cannot ensure its integrity. For instance, Sparrow [13] (used by Contiki) only verifies the CRC of the image to detect errors during transmissions.

On the other hand, recent firmware update solutions like SUIT [14] or UpKit [7] need to have an additional trust anchor (e.g., a signing certificate on the IoT device) or dedicated hardware, e.g., a Trusted Execution Environment [15], to allow verifying the integrity of the image. Nevertheless, the impairment of the supply chain or the delivery mechanism (e.g., the update server or the companion mobile app) could allow an attacker to inject a crafted firmware into the delivery pipeline, such as the firmware modification attack reported on commercial fitness trackers in [1].

Finally, existing solutions lack the support of the manual update of the device, where the owner directly loads a firmware image without any assurance of its authenticity.

In this work, we will investigate the impact of repackaging attacks on IoT firmware, thereby discussing security threats that harm its integrity. Then, we will point out the limitations of the state-of-the-art integrity checking mechanisms that are enforced during IoT firmware updates and on the device.
Finally, we will present PATRIOT, a novel self-integrity protection mechanism for IoT firmware that automatically spots altered firmware images without the need for device trust anchors, external agents, or network connectivity. Briefly, PATRIOT focuses on inserting encrypted detection nodes (called cryptographically obfuscated logic bombs [16]) that embed integrity checks on the content of the firmware, called anti-tampering (AT) controls. The detection nodes are triggered during the execution of the firmware, and if some tampering is detected, the firmware is usually forced to crash. The rationale is to discourage the attacker from repackaging if the likelihood of building a working repackaged firmware is low.

PATRIOT supports the automatic protection of firmware to detect and prevent anti-repackaging attacks introduced during the firmware production and delivery process. To experimentally evaluate the feasibility of PATRIOT, we implemented it in a tool for C/C++ firmware (i.e., PATRIOTIC) that we leveraged to test the methodology against a dataset of 33 firmware samples based on RIOT OS. The tool achieved the 84.3% of success rate and required - on average - only 70.3 seconds per firmware to introduce the protections. Moreover, we evaluated the reliability of PATRIOT by testing the repackaging detection capabilities of the protected firmware at runtime. The preliminary results showed that our solution ensures high compatibility with existing firmware generation and delivery processes and a high detection rate of repackaging attacks.

Structure of the paper. First, we will introduce the concept of firmware repackaging in the IoT ecosystem (Section II). Then, we will focus on the integrity threats that could affect the firmware production and delivery process, thereby highlighting the limitations of state-of-the-art approaches (Section III). Then, we will present the PATRIOT protection scheme, its distinguishing features, and its runtime behavior (Section IV). In Section V we will present the PATRIOTIC implementation and, in Section VI, we will detail the experimental campaign on 33 firmware based on RIOT OS. Finally, in Section VII we will conclude the paper by summing up the main takeaways and putting forward some consideration for future works.

II. Firmware Repackaging

Firmware repackaging [17] is an attack devoted to tamper a legitimate firmware and redistribute the modified - i.e., repackaged - version to IoT devices to perform further attacks. Repackaging attacks to IoT firmware are motivated by at least one of the following reasons:

a) Unauthorized access/usage: the attacker modifies the firmware to bypass the predefined software access control privileges, e.g., to gain access to privileged functionalities or classified data.

b) Unlicensed clones: the attacker’s goal is to reuse the firmware crucial processes in some other programs. To this aim, part of the firmware image can be extracted and partially reused by the attacker to craft a clone of the original version [18].

c) Malware injection: by injecting malicious code, the attacker aims to breach the firmware integrity, thereby illegally altering the firmware behavior. In such a case, the compromised firmware can disrupt the trustworthiness of an IoT device [19].

d) Disrupting the system availability: the attacker aims to reduce the system availability, injecting code in the firmware image able to cause system halting (like DoS Attack) or significant delays in the regular operation of an IoT device.

A firmware repackaging attack can be summarized in the sequence of steps depicted in Figure 1.

The first phase consists of the retrieval of the original firmware image (Step 1). Attackers can get hold of the firmware by: i) dumping it using the physical/remote access interfaces of an IoT device [20], ii) sniffing the package during an OTA update [10], or iii) downloading it from the vendor’s website, support and community forums or public repositories.

Once the firmware image is obtained, the attacker applies reverse engineering techniques (Step 2) to understand the application logic and extract sensitive information such as encryption keys, hard-coded credentials, or sensitive URLs. Then, she can proceed with the injection phase using binary rewriting techniques [21] (Step 3). During this phase, the attacker injects custom code (e.g., malware) or modifies the existing binary image to alter the original behavior. Finally, the modified image can be repacked in the original format (Step 4). The repackaged firmware is then ready to be redistributed in the delivery pipeline or installed directly on a target device.

III. Firmware Delivery and Integrity Threats

The typical firmware production and delivery process is summarized in Figure 2. The first steps are devoted to the production of the firmware (generation phase), i.e., the building of the software bundle containing all the software that ensures the functioning of the IoT device.

The firmware supply chain - even for a relatively simple, single-processor device - consists of many software providers, including chip vendors, tool vendors, and companies that provide the different software components. In the case of Figure 2 the software supply chain is composed of three actors providing the OS, the device drivers, and the application, which delivers the device core functionalities, respectively.
The different pieces of software are then composed by the Firmware Manufacturer (FM), which generates the firmware image and some metadata information, like a digitally-signed manifest file, used to evaluate the success of the delivery phase. At the end of the generation phase, the firmware is released on a centralized repository (e.g., an IoT Firmware Update Server).

The firmware delivery process (distribution phase) can occur either manually or by employing an automated firmware update process. In the first case, users get the firmware from the firmware repository and distribute it to the IoT devices by using over-the-air (OTA) technologies (e.g., Bluetooth LE or Wi-Fi) or physical interfaces (e.g., UART or USB ports). For such a task, the user may also rely on a Mobile Update Agent (MUA), i.e., a companion mobile app (e.g., Samsung SmartThing) that acts as a gateway between the update server and the IoT device. After receiving an update notification, the MUA downloads the software update and verifies its integrity, e.g., by checking the consistency between the digitally-signed manifest file and the software package. Once the verification succeeds, the MUA sends the update to the Firmware Consumer using low-power radio technologies.

In the automated distribution phase, instead, the firmware is distributed to the IoT devices by using client-server architectures (e.g., SUIT) or distributed solutions (e.g., [22]). If this is the case, the IoT Firmware Update Server interacts through an access point with the device.

The last step in the firmware update is the loading phase. An agent placed on the device (i.e., the Firmware Consumer) receives the software bundle and the metadata, and copies the update image in the correct memory address to proceed with the installation. Such a step may involve a further verification of the correctness of the received data, e.g., through a hash check or signature verification.

A. Threats to the Firmware Integrity

The security threats involving the integrity of firmware bundles can occur in all the three stages of the production and delivery process.

Indeed, during the generation phase, several parts of the software are typically provided in a black-box fashion, i.e., closed-source and in an executable format. Also, software producers are not in control of the entire pipeline and, thus, they do not have any assurance that their software won’t be delivered unaltered [17].

During the firmware delivery phase, an attacker can exploit a set of security threats to retrieve the original firmware or inject the repackaged one. For instance, an attacker may eavesdrop on the untrusted network communication channel. In such a scenario, an intruder can take hold of the firmware image, extract sensitive data from it, and the file can be modified and returned for distribution [11].

Furthermore, in a client-server model, a server manages all the data it stores, so a firmware file can be forged into a malicious file before being distributed. An adversary may also compromise the server to delete the latest firmware file, inject a malicious file [22], or overload the server to interfere with the update process [23]. An attacker can also compromise the device used to transmit the update, e.g., the MUA or the access point, to break the correct verification or delivery process. For instance, Schüll et al. [24] showed a new firmware modification attack against a fitness tracker, where an adversary manipulated plain HTTP traffic and TLS proxy between an original gateway and the update server.

Finally, in the loading phase an attacker having physical access to the device, may disable its security mechanisms or hardware locks [17]. In such a scenario, the attacker can remove/modify the trust anchor (e.g., change the signing certificate) and inject a repackaged firmware.

After the firmware has been securely delivered to the IoT device, then the firmware needs to be flashed. Before it gets flashed, possible attacks could happen, such as time-of-check-
to-time-of-use attacks (TOCTOU) [11], where an attacker modifies the firmware after the verification process but before the firmware has been flashed to memory.

B. Related Work on Firmware Verification

Operating systems designed explicitly for constrained IoT devices (e.g., TinyOS [30] and Contiki [31]) often embed or can be extended with over-the-air reprogramming capabilities. Still, many of the existing solutions focus only on a portion of the update process or do not carry out a proper verification of the downloaded firmware and hence cannot ensure its integrity. This indeed results in OSes without an update system (e.g., NutX [24]) or with an incomplete one. For instance, Sparrow [13] (used by Contiki), and Deluge [26] (used by TinyOS) only verify the CRC to ensure the integrity of the firmware during transmissions, without any integrity validation during the generation and loading phases.

To this aim, the research community has been working on the definition of secure IoT update processes [27]. For instance, [28], [29], and [30] proposed secure extensions for Deluge, that provide integrity assurance for the firmware image and resilience against DoS attacks that specifically target firmware dissemination protocols.

Other solutions, like UpKit [7] or ASSURED [15], put forward a scalable and lightweight solution able to securely perform software updates across different OSes and hardware platforms that support end-to-end security. Also, the authors in [31] propose a secure firmware update mechanism for the constrained IoT devices based on open standards such as CoAP, LwM2M, and SUIT.

However, most of the existing solutions focus only on the delivery and loading phase of the process, leaving the software providers and the FM unprotected against attacks during the generation phase. If this is not the case, they still require an external trust anchor, e.g., a Trustzone [15] or a signing certificate, to grant the integrity of the delivered update. To overcome such limitations, in this paper we will present PATRIOT, the first methodology that ensures the integrity of the firmware update relying on a self-protection mechanism.

IV. PATRIOT

In this section, we introduce the basics of PATRIOT (Pervasive Anti-Tampering and Anti-Repackaging for IoT), the first solution aimed at making IoT firmware self-resistant against repackaging through the whole production and delivery process. PATRIOT protects an IoT firmware by injecting self-protecting code directly inside the firmware code.

The methodology exploits the use of cryptographically obfuscated logic bombs (CLB) [16] to hide anti-tampering (AT) checks in the firmware executable. Such CLBs will be triggered (i.e., explode) in case of any tampering is detected. The rest of this section details the concepts of CLB and AT checks, the PATRIOT protection scheme, and its runtime behavior.

A. Logic Bombs and Anti-Tampering Checks

A logic bomb is a piece of code that is executed when specific conditions are met. While logic bombs are widely used by malware to introduce and trigger malicious conditions inside apparently unarmed code [32], [33], this technique can also be used to include tampering detection code (namely, AT checks) inside the activated bomb.

In a nutshell, anti-tampering checks are self-protecting functions which aim to detect modifications in a piece of software. To this goal, AT checks may verify at runtime some relevant information of the code or the executable file against precomputed values. Currently, there exist several methods to detect tampering in executable files, as highlighted in [34].

To hide the behavior inside a logic bomb, [10] introduced the concept of cryptographically obfuscated logic bomb. The deployment of a CLB (Listing 1) consists in replacing a qualified condition (QC) - i.e., a condition containing an equality check, where one of the operands is a constant value (e.g., $X == const$) - in a branch.

The original condition is transformed in a new one where the pre-computed hash value of the constant (i.e., $H(const)$) is compared with the result of the hash function applied to variable $X$ plus some salt. Besides, the original content of the qualifying condition is extended with one or more AT checks and encrypted using the $const$ value as the encryption key (i.e., $encrypted\_content$). If the triggering condition is met, the $X$ value is used to decrypt the $encrypted\_content$, and, thus, to launch the bomb.

```
if(H(X, salt) == Hconst)
{
    body = decrypt(encrypted_content, X);
    execute(body);
}
```

Listing 1: Example of Cryptographically Obfuscated Logic Bomb (CLB).

The protection of the CLB is granted by the one-way property of cryptographic hash functions, that makes hard for the attacker to retrieve the original $const$ value (i.e., the decryption key) from its hash. To defuse an AT check inside a CLB, an attacker has to execute the CLB, retrieve the value of the decryption key, decrypt the corresponding $encrypted\_content$, and then bypass or remove the AT checks injected in the body of the qualified condition.

B. Protection Scheme

The PATRIOT protection scheme is based on the dissemination in the IoT firmware of CLBs that hide a set of AT checks. To minimize the complexity, each CLB embeds a single AT check that performs a signature verification of a portion of the IoT firmware executable. Still, it is worth noticing that PATRIOT supports the definition of other AT checks as well as different CLB schemes.

Figure 3 shows a high-level overview of the protection process and the runtime behavior of the proposed technique. PATRIOT starts the protection process from the source code of the IoT firmware. In detail, it parses the source code (Step 1) to identify the set of suitable qualified conditions (Step 2). In Step 3, these conditions are transformed according to the
Fig. 3: High-level overview of PATRIOT protection process and runtime behavior of a protected firmware.

CLB. During this process, the equality check of the QC is transformed in the cryptographically obfuscated form (Step 3.1). Then, PATRIOT extracts the body of the qualified condition (Step 3.2), injects the AT code (Step 3.3), and adds the logic to decrypt and execute the new body once in the encrypted form (Step 3.4).

Once the firmware goes through the compilation process, PATRIOT completes the protection process (Steps 4-5). In detail, the scheme computes the digest values for all the injected AT checks, storing their values inside the corresponding bombs. Finally, PATRIOT encrypts each CLB with their const values to obtain the protected firmware.

C. Runtime Behavior

At runtime, the code of the CLBs is executed iff the value of the variable in the QC is equal to the constant value (i.e., if its hash is equal to $H_{const}$ - Step 6). If this is the case, the body of the CLB is decrypted using the $const$ value as decryption key (Step 7), and the corresponding code is executed. This behavior triggers the AT check (Step 8) that computes the digest of a portion of the firmware code and compares it with the stored one. If these values match, the execution can proceed normally (Step 9a). Otherwise, the AT reports a tampering attempt and executes an action, like send an alert to the Firmware Manufacturer or triggers a Security Exception and abort the execution (i.e., the case of Step 9b).

V. PATRIOTIC

To demonstrate the applicability and the feasibility of PATRIOT, we developed PATRIOTIC (i.e., PATRIOT for Integrated C-based Firmware) to support the protection of IoT firmware designed in C/C++ programming language. The tool is publicly available on GitHub at [35]. PATRIOTIC consists of two main modules:

- CLB Injector. This module works directly on the firmware source code and is responsible for parsing of the source code, detect the QCs, and build of CLBs (Steps 1-3 of the protection process).
- CLB Protector. This module processes the compiled IoT firmware and it is responsible for computing the signature-verification digests of AT checks and encrypting the CLBs (Steps 4-5 of Figure 3).

A. CLB Injector

CLB Injector is built using the Python language and leverages the Clang library[2] to pre-process the C/C++ source code. During this phase, CLB Injector scans the source code to obtain the list of qualified conditions that can host a logic bomb. In the current implementation, CLB Injector supports if-then-else statements with an equality condition of the form of $X == const$. If we consider the source code of Listing 2 as an example, CLB Injector would detect one QC at row 7.

```python
int funA(int val); void funB(int val) {
    int a = 0;
    [...] /
    if (a == CONST) {
```

[2]: https://github.com/llvm-mirror/clang/tree/master/bindings/python
After the QC detection phase, CLB Injector converts each QC in the corresponding CLB. To do so, the tool computes the hash of the constant value of the QC, generates a 4-bytes random salt, and modifies the if condition to match the form if($H(X,salt) == H\text{const}$). Then, it creates a new function (ext\_fun) that encapsulates the QC original body and accepts - as input parameters - all the variables used inside the body. Moreover, during this phase, the module adds an AT control in ext\_fun (Step 3.3 of Figure [3]). In the current implementation, the AT control evaluates the hash signature of a portion of the compiled firmware and raises a security exception in case of a signature mismatch.

Since CLB Injector works directly on the source code, it injects three placeholders values into the source code that will be updated by CLB Protector before the encryption phase. In detail, the module adds three variables, i.e., offset and count, to identify the part of the executable to evaluate in the AT control, and the expected result of the verification (i.e., control\_value).

Finally, CLB Injector injects in the body of the CLB the functions to decrypt and execute ext\_fun.

Listing 3 reports the processing result of CLB Injector on the example code of Listing 2. Starting from the QC located in funB, CLB Injector creates a new function (ext\_funB) that contains the original body of the QC (rows 3-13). Then, it injects an anti-tampering control (row 9) that verifies a portion of the executable file (identified by offset and count - rows 5 and 6) against the expected hash value (i.e., the variable control\_value - row 7). Finally, CLB Injector replaces the original body of the QC with the code to decrypt and execute the original function (rows 20 and 21).

```
/* or_code */
int res = funA(val);
printf("The result is %d\n", res);

Listing 2: Example of a C source code.
```

Fig. 4: CLB Protector protection process on the part of the executable file containing ext\_funB of Listing 3.

### B. CLB Protector

CLB Protector is a Java command-line tool that processes the compiled IoT firmware to i) update the control values of the AT checks, and ii) encrypt the content of the CLBs. The module receives from CLB Injector the list of CLBs, the functions that need encryption (i.e., the list of ext\_fun methods), and their corresponding encryption keys (i.e., the const values).

For each CLB, the tool exploits nm [1] to locate in the firmware executable the corresponding ext\_fun and the position of the embedded control values (i.e., offset, count, and control\_value). Also, the module identifies the portion of code that will be evaluated by the AT checks. The current version of CLB Protector selects - starting either from the beginning or the end of the file - the compiled code until it reaches the first unencrypted ext\_fun (i.e., that still needs to be processed). From the selected code, the module computes: i) the starting position (offset), ii) the number of bytes (code), and iii) the hash of the selection (control\_value). Then, CLB Protector replaces the placeholder values with the obtained results (Step 4 of Figure 4). Finally, CLB Protector encrypts the bytes of the ext\_fun using the const value as the encryption key (step 5).

Figure 4 shows the protection applied by CLB Protector on the part of the executable file containing ext\_funB of Listing 3. In detail, the tool locates the control values (Fig. 4a), computes and updates their values (Fig. 4b), and, then, encrypts the entire function (Fig. 4c).
We empirically tested the performance of the PATRIOT methodology by i) applying PATRIOTIC over a dataset of 33 firmware samples to evaluate the distribution of the protection controls, and ii) executing both the original and the protected firmware to evaluate their runtime behavior and the introduced size overhead. Finally, we evaluated the reliability of the protection against actual repackaging attacks by attempting to repackage each of the protected firmware and testing the tampered file.

The experiments were hosted on a virtual machine running Ubuntu 20.04 with 8 processors and 32GB RAM. Each firmware is built using RIOT OS version 2021.05 and a different RIOT app (downloaded from [36]). RIOT is an open source OS designed for resource constrained IoT devices that has gained the attention of the scientific community in the last years [37]. RIOT OS allows for standard C and C++ programming, provides multi-threading as well as real-time capabilities, and needs only a minimum of 1.5 kB of RAM. Hereafter, we refer to each firmware with the name of the contained application.

### A. Protection evaluation

PATRIOTIC was able to apply the protections over the entire dataset in nearly 39 minutes (i.e., 2310 seconds) of computation. The protection of a single firmware took, on average, 70.3 seconds.

PATRIOTIC worked successfully in 84.8% (28/33) of the cases, i.e., it generated a valid protected firmware. The remaining 15.2% (i.e., 5 cases) failed due to errors in the building phase. We manually investigated such problems to discover that the build process failed due to the presence of at least an ext_fun with i) unsupported instructions (e.g., goto statements to undefined portions of code), or ii) undefined variables. These problems are mainly related to the parsing of the source code (i.e., Step 1 of Figure 5) that lead to an incorrect identification of the body of the QCs.

Figure 5 shows the number of logic bombs distributed in each protected RIOT firmware. PATRIOTIC injected, on average, 42.1 CLBs with a standard deviation of 12.1. Moreover, Figure 5 also highlights that the minimum and maximum number of injected controls are 28 and 68, respectively.

Figure 6 shows the percentage size overhead introduced by the protection on the firmware executable. In particular, the minimum and maximum size overhead are respectively 3.49% and 15.77%, with an average of 11.13% and a standard deviation of 3.08%. It is worth noticing that this corresponds to a size overhead always below 172.6KB, with an average size overhead of 115.2KB and a standard deviation of 39.5KB.

We empirically tested the protected firmware at runtime to verify that the introduced protections did not harm the normal functioning of the software bundle. To do so, we executed the 28 protected firmware compiled for a native board (i.e., an emulated board that can be executed on the host machine [38]), and we injected a sequence of random user inputs. The experimental evaluation reported that all the protected firmware samples executed correctly, i.e., they did not crash nor trigger exceptions.
C. Prototype Limitations

The experimental campaign led to the identification of some limitations of PATRIOTIC that will be discussed below. In the current implementation, CLB Injector injects the functions to decrypt and execute `ext_fun` as static methods in each file that contains at least a CLB. Such a choice allows reducing the complexity of injecting and referencing a third-party module inside the existing firmware at the cost of introducing potentially redundant code.

The experimental results also highlighted a direct correlation between the complexity of the `const` value used as the encryption key and the hiding capability offered by the CLBs. For instance, we discovered that many constant values in the RIOT OS are 2 bytes values, thus limiting the resiliency of PATRIOTIC against brute force attacks to guess the encryption key and bypass the CLBs. To overcome this limitation, PATRIOTIC could be extended to detect different types of logic bombs, such as QCs containing a string comparison function like `strcmp()` and `strncmp()`. Also, the current version of PATRIOTIC supports only the xor-cipher algorithm to encrypt the CLBs. We planned to investigate other state-of-the-art algorithms for the encryption and hashing phase, such as AES and SHA.

Finally, the `nm` tool - used to detect the `ext_fun` functions in the executable file - requires the firmware to be built with debugging symbols. As future work, we planned to investigate the usage of other tools to protect the firmware executable without symbols. It is worth pointing out that a firmware developer can use several tools, such as `strip` to remove symbols and additional data from object files even after the protection process.

VII. Conclusion

In this work, we proposed PATRIOT, a self-protection mechanism that ensures the integrity of IoT firmware through the entire production and delivery process. PATRIOT injects CLB and AT controls directly in the firmware binary without the need for external trust anchors or verification processes. Furthermore, we implemented PATRIOT in a tool for protecting C/C++ firmware, called PATRIOTIC, that is publicly available on GitHub. The evaluation of 33 firmware samples for RIOT OS demonstrated the applicability and the efficacy of the tool and the proposed protection scheme.

As a future extension of this work, we plan to i) extend the protection scheme by adding multi-patter (i.e., heterogeneous) AT controls, ii) evaluate the computational and energy footprint of the protection scheme on resource-constrained IoT devices, and iii) add the support to other programming languages and OSes.

REFERENCES

[1] J. Shim, K. Jung, S. Cho, M. Park, and S. Han, “A case study on vulnerability analysis and firmware modification attack for a wearable fitness tracker,” *IT Converg. Pract.*, vol. 5, no. 4, pp. 25–33, 2017.

[2] E. Baccelli, O. Hahm, M. Günes, M. Wählisch, and T. C. Schmidt, “Riot os: Towards an os for the internet of things,” in *2013 IEEE conference on computer communications workshops (INFOCOM WSHPS)*. IEEE, 2013, pp. 79–80.

[3] A. Dunkels, B. Gronvall, and T. Voigt, “Contiki-a lightweight and flexible operating system for tiny networked sensors,” in *29th annual IEEE international conference on local computer networks*. IEEE, 2004, pp. 455–462.

[4] Y. David, N. Parrish, and E. Yahav, “Firmup: Precise static detection of common vulnerabilities in firmware,” *ACM SIGPLAN Notices*, vol. 53, no. 2, pp. 392–404, 2018.

[5] A. Costin, A. Zarras, and A. Francillon, “Automated dynamic firmware analysis at scale: a case study on embedded web interfaces,” in *Proceedings of the 11th ACM on Asia Conference on Computer and Communications Security*, 2016, pp. 437–448.

[6] N. Dejon, D. Caputo, L. Verderame, A. Armando, and A. Merlo, “Automated security analysis of iot software updates,” in *IFIP International Conference on Information Security Theory and Practice*. Springer, 2019, pp. 223–239.

[7] A. Langiu, C. A. Boano, M. Schüß, and K. Römer, “Upkit: An open-source, portable, and lightweight update framework for constrained iot devices,” in *2019 IEEE 39th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2019, pp. 2101–2112.

[8] https://man7.org/linux/man-pages/man1/strip.1.html
DroneBl, “Network Bluepill,” [http://www.dronebl.org/blog/8](http://www.dronebl.org/blog/8), 2008, [Online; accessed September 10, 2021].

E. Ronen, A. Shamir, A.-O. Weingarten, and C. O’Flynn, “Iot goes nuclear: Creating a zigbee chain reaction,” in 2017 IEEE Symposium on Security and Privacy (SP). IEEE, 2017, pp. 195–212.

A. Gupta, The IoT Hacker’s Handbook. Springer, 2019.

N. S. Mietwa, P. Tarwireyi, A. M. Bub-Mahfouz, and M. O. Adigun, “Secure firmware updates in the internet of things: A survey,” in 2019 International Multidisciplinary Information Technology and Engineering Conference (IMITEC). IEEE, 2019, pp. 1–7.

A. Merlo, A. Ruggia, L. Sciolla, and L. Verderame, “You shall not repack! de-mystifying anti-re-packaging on android,” Computers & Security, vol. 103, p. 102181, 2021.

R. SICS, “The Sparrow Application Layer and Tools,” [https://github.com/sics-iot/sparrow](https://github.com/sics-iot/sparrow), 2018, [Online; accessed September 10, 2021].

L. E. T. F. (IETF), “Software Updates for Internet of Things (suit),” [https://datatracker.ietf.org/wg/suit/documents/](https://datatracker.ietf.org/wg/suit/documents/), 2018, [Online; accessed September 10, 2021].

N. Asokan, T. Nyman, N. Rattanavipanon, A.-R. Sadeghi, and G. Tsudik, “Assured: Architecture for secure software update of realistic embedded devices,” IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 37, no. 11, pp. 2290–2300, 2018.

Q. Zeng, L. Luo, Z. Qian, X. Du, and Z. Li, “Resilient decentralized android application repackaging detection using logic bombs,” in Proceedings of the 2018 International Symposium on Code Generation and Optimization, ser. CGO 2018. New York, NY, USA: Association for Computing Machinery, 2018, p. 50–61. [Online]. Available: [https://doi.org/10.1145/3168680.3203141](https://doi.org/10.1145/3168680.3203141).

A. C. Panchal, V. M. Khadse, and P. N. Mahalle, “Security issues in iot: A comprehensive survey of attacks on iot and its countermeasures,” in 2018 IEEE Global Conference on Wireless Computing and Networking (GCWN). IEEE, 2018, pp. 124–130.

A. A. A. Al-Wosabi, Z. Shukur, and M. A. Ibrahim, “Framework for software tampering detection in embedded systems,” in 2015 International Conference on Electrical Engineering and Informatics (ICEEI). IEEE, 2015, pp. 259–264.

ZDNet, “Surveillance cameras sold on Amazon infected with malware,” [https://www.zdnet.com/article/amazon-surveillance-cameras-infected-with-malware/](https://www.zdnet.com/article/amazon-surveillance-cameras-infected-with-malware/), 2016, [Online; accessed September 10, 2021].

S. Vasilie, D. Oswald, and T. Chothia, “Breaking all the things—a systematic survey of firmware extraction techniques for iot devices,” in International Conference on Smart Card Research and Advanced Applications. Springer, 2018, pp. 171–185.

M. Wenzl, G. Merzdonvnik, J. Ullrich, and E. Weippl, “From hack to elaborate technique—a survey on binary rewriting,” ACM Computing Surveys (CSUR), vol. 52, no. 3, pp. 1–37, 2019.

S. Choi and J.-H. Lee, “Blockchain-based distributed firmware update architecture for iot devices,” IEEE Access, vol. 8, pp. 37518–37525, 2020.

K. Zandberg, K. Schleifer, F. Acosta, H. Tschofenig, and E. Baccelli, “Secure firmware updates for constrained iot devices using open standards: A reality check,” IEEE Access, vol. 7, pp. 71907–71920, 2019.

N. D. Schull, “Data for life: Wearable technology and the design of self-care,” BioSocieties, vol. 11, no. 3, pp. 317–333, 2016.

A. Foundation, “Nuttx OS,” [https://nuttx.apache.org/](https://nuttx.apache.org/), 2018, [Online; accessed September 10, 2021].

J. W. Hui and D. C. Chu, “The dynamic behavior of a data dissemination protocol for network programming at scale,” in Proceedings of the 2nd international conference on Embedded networked sensor systems, 2004, pp. 81–94.

K. Arakadakis, P. Charalampidis, A. Makrogianakis, and A. Fragiadakis, “Firmware over-the-air programming techniques for iot networks—a survey,” arXiv preprint arXiv:2009.02260, 2020.

S. Hyun, P. Ning, A. Liu, and W. Du, “Seluge: Secure and dos-resistant code dissemination in wireless sensor networks,” in 2008 International Conference on Information Processing in Sensor Networks (ipsn 2008). IEEE, 2008, pp. 445–456.

P. E. Lanigan, R. Gandhi, and P. Narasimhan, “Stlucie: Secure dissemination of code updates in sensor networks,” in 26th IEEE international conference on Distributed Computing Systems (ICDCS’06). IEEE, 2006, pp. 53–53.

P. K. Dutta, J. W. Hui, D. C. Chu, and D. E. Culler, “Securing the deluge network programming system,” in 2006 5th International Conference on Information Processing in Sensor Networks. IEEE, 2006, pp. 326–333.

K. Zandberg, K. Schleifer, F. Acosta, H. Tschofenig, and E. Baccelli, “Secure firmware updates for constrained iot devices using open standards: A reality check,” IEEE Access, vol. 7, pp. 71907–71920, 2019.

Y. Fratantonio, A. Bianchi, W. Robertson, E. Kirda, C. Kruegel, and G. Vigna, “Triggerscope: Towards detecting logic bombs in android applications,” in 2016 IEEE Symposium on Security and Privacy (SP), 2016, pp. 377–396.

D. Brumley, C. Hartwig, Z. Liang, J. Newsome, D. Song, and H. Yin, “Automatically Identifying Trigger-based Behavior in Malware,” Boston, MA: Springer US, 2008, pp. 65–88. [Online]. Available: [https://doi.org/10.1007/978-0-387-68768-1](https://doi.org/10.1007/978-0-387-68768-1).

M. Almadviand, A. Pretschner, and F. Kelbert, “Chapter eight - a taxonomy of software integrity protection techniques,” ser. Advances in Computers, A. M. Memon, Ed. Elsevier, 2019, vol. 112, pp. 413–486. [Online]. Available: [https://www.sciencedirect.com/science/article/pii/S0065245817300591](https://www.sciencedirect.com/science/article/pii/S0065245817300591).

Computer Security Laboratory, “Patriot,” [https://github.com/iot-security/patriot](https://github.com/iot-security/patriot), 2021, [Online; accessed September 10, 2021].

Riot OS, “Riot Sample Apps,” [https://github.com/riot-os/riot/tree/master/examples](https://github.com/riot-os/riot/tree/master/examples), 2021, [Online; accessed September 10, 2021].

E. Baccelli, C. Gündoğan, O. Hahm, P. Kietzmann, M. S. Lenders, H. Petersen, K. Schleifer, T. C. Schmidt, and M. Wählisch, “Riot: An open source operating system for low-end embedded devices in the iot,” IEEE Internet of Things Journal, vol. 5, no. 6, pp. 4428–4440, 2018.

Riot OS, “Native Board,” [https://api.riot-os.org/group_board native.html](https://api.riot-os.org/group_board native.html), 2021, [Online; accessed September 10, 2021].

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