Beware of the App! On the Vulnerability Surface of Smart Devices through their Companion Apps

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Abstract—Internet of Things (IoT) devices are becoming increasingly important. These devices are often resource-limited, hindering rigorous enforcement of security policies. Assessing the vulnerability of IoT devices is an important problem, but analyzing their firmware is difficult for a variety of reasons, including requiring the purchase of devices. This paper finds that analyzing companion apps to these devices for clues to security vulnerabilities can be an effective strategy. Compared to device hardware and firmware, these apps are easy to download and analyze. A key finding of this study is that the communication between an IoT device and its app is often not properly encrypted and authenticated and these issues enable the construction of exploits to remotely control the devices. To confirm the vulnerabilities found, we created exploits against five popular IoT devices from Amazon by using a combination of static and dynamic analyses. We also did a larger study, finding that analyzing 96 popular IoT devices only required analyzing 32 companion apps. Among the conservative findings, 50% of the apps corresponding to 38% of the devices did not use proper encryption techniques to secure device to companion app communication. Finally, we discuss defense strategies that developers can adapt to address the lessons from our work.

Index Terms—Security; Internet of Things; Android Apps; Companion Apps

I. INTRODUCTION

The number of Internet of Things (IoT) devices worldwide is predicted to reach 20 billion by 2020 [1]. Designing secure solutions in this domain is challenging as devices are typically limited in resources. Consequently, security is a permanent concern. As a concrete example, in October 2016, the Mirai malware compromised millions of IoT devices around the world and used them to launch the largest DDoS attack ever recorded [2]. In the smart-home scenario, security vulnerabilities in IoT devices could compromise safety at home [3].

IoT devices are compatible with multiple cloud-based software stacks (e.g., SmartApps in the SmartThings cloud [4], Alexa Skills [5], etc.). Prior work has found security vulnerabilities introduced by some of these stacks [6, 7]. Unfortunately, a gap remains in that the device may have vulnerabilities out-of-the-box that are independent of security of high-level software stacks. Unfortunately, techniques for security analysis of device software itself remains an art and poorly understood. For example, a white paper by Veracode describes vulnerabilities in 6 IoT devices, including SmartThings Hub, Wink Hub, Wink Relay, and MyQ Garage, but not how to analyze such vulnerabilities in a systematic way. One solution would be for a security analyst to inspect the firmware binary on the device, but that is often hard to access [8] and challenging to analyze [9].

This paper proposes an indirect and simpler way of assessing the security of IoT devices by analyzing their companion apps and the interaction with the device’s firmware. Our intuition is that if this interaction between the companion app and device firmware is not implemented with good security principles, the device’s firmware is potentially insecure and vulnerable to attacks. In our experience, most IoT devices on the market today are released with companion apps for both Android and iOS so that users could control these devices directly from their smartphone, thus permitting such analysis.

Our hypothesis is that the analysis of these apps can throw substantial light on potential vulnerabilities in devices and even help security analysts develop proof-of-concept exploits to induce the device manufacturers to verify the vulnerabilities and fix them. To validate the hypothesis, we analyze multiple smartphone apps to discover potential vulnerabilities and, from that, create proof-of-concept attacks that could allow either a local or remote attacker to completely compromise the device, including issuing arbitrary commands to them or update their firmware without ever touching the device physically. These apps play an important role in the secure operation of smart devices. In particular, they are responsible for the initial device configuration, i.e., these apps set up the communication channel with the device with supposedly proper encryption and authentication. Because of this important role, IoT apps need to encode sensitive communication data, such as the type of encryption being used, and even encryption keys. This information can be valuable for an attacker who wants to gain control of the device. Moreover, in contrast to physical devices, these apps are accessible to the general public through market places (e.g., Google Play). It is, therefore, a sweet spot for hackers to focus their efforts on.

In the security analysis of the smartphone apps, we particularly focus on the security of communication between an IoT device and its app. Any flaws could enable a range of attacks that can result in complete control of the IoT device.
We analyzed smartphone apps for 96 of top-selling WiFi and Bluetooth-enabled devices on Amazon. There were 32 unique apps for these devices (e.g., devices were from the same vendor and sometimes different vendors shared apps) and then developed proof-of-concept attacks on 5 of the devices. For example, we find that an Amazon top-seller smart plug from TP-Link [10] shares the same hard-coded encryption key for all the devices of a given product line and that the initial configuration of the device is established through the app without proper authentication. Using this information, we were able to create a spoofing attack to gain control of this device.

Note that this issue can be replicated in all other TP-Link devices that use the same app.

This paper makes the following contributions:

Empirical Study. We show the value of analyzing companion apps as a useful vulnerability analysis technique for devices by conducting two studies to assess the security of app-device communication by analyzing companion apps corresponding to the device. These studies consider key security aspects in this context, namely, encryption, authentication, and network protocols. The first study involved a detailed analysis of four different apps (for five devices, with two devices sharing an app) and then creating concrete exploits. A second study analyzed 32 apps for 96 devices to find extent of similar features that could potentially enable an exploit.

Efficiency. We found that we only had to analyze 4 apps for the 5 devices actually purchased and 32 apps for 96 devices overall. There was extensive sharing of apps among devices. Thus, it can be significantly more efficient to analyze companion apps as compared to device firmware.

Findings and Lessons. We found lack of encryption in 31% of the apps analyzed and use of hardcoded keys in 19% of all the apps—thus, at least 50% of the apps were potentially seriously vulnerable to exploits (these apps corresponded to 37 out of 96 devices considered). Many of these apps controlled their devices via local communication or via broadcast messages, including UDP messages. Based on our in-depth analysis of 4 of the apps, we found that leveraging these weaknesses to create actual exploits is not challenging. A remote attacker simply has to find a way of getting the exploit either on the user’s smartphone in the form of an unprivileged app or a script on the local network. We then discuss potential defense strategies.

Spoofing Attacks. We provide detailed evidence of the importance of our findings by building proof-of-concept attacks on randomly selected, from a list of popular IoT devices on Amazon, five IoT devices. We purchased these devices prior to the analysis. We were successful in creating attack apps (or scripts) that could execute arbitrary commands on the device. The attacks were successful even if the device had previously been paired with a legitimate app.

II. Context, Goal, and Questions

A. Context

Most manufacturers of IoT devices provide a smartphone application and cloud services to monitor and control their devices. Communication between the device and its companion app is often established over the local network using some wireless protocol such as Zigbee and Z-Wave [11]. When the device and the smartphone are in distinct networks or the IoT setup does not support local network connectivity, the cloud server acts as a proxy for communication. An IoT app sends the message intended for a device to the cloud server and the cloud server relays the message to the device. Similarly, a message from a device can be relayed to the IoT app through the cloud. Figure 1 illustrates an example setup with a router/hub and with the cloud. Setups without one or both of these elements are possible. For example, it is possible that only local communication is allowed (i.e., no cloud) and that the app and the device communicate directly (i.e., through the router). Hubs are especially useful to enable communication with resource-constrained devices that do not need to fully implement a network stack.

In this context, pairing is the process of establishing a communication channel between an app and a device. A prevalent hypothesis made by users is that, once established, this channel is secure. The goal of this paper is to assess this hypothesis, i.e., this study evaluates whether the app-device channel is properly secured. To achieve this goal we analyze companion apps for vulnerabilities and then confirm them by creating exploits. We make the following assumptions on these exploits:

- that an adversary has access to the local network;
- that an adversary uses a rogue app or script to control the device without user knowledge.

To illustrate a potential use case for such exploits, consider, for instance, the scenario of a burglar trying to break into your smart home. The first step is to gain access to your WiFi network using some public technique [13]. The burglar does not need to succeed in all attempts. The next step is to detect

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1A video illustrating a counterfeit app in action can be found at [https://tigshare.com/s/659c4302f75272d55885f]

2Tuya Smart [12] is an example framework where the companion app can only communicate with the device through the cloud.
periods of time when the house would be empty. For that, the burglar could monitor the network and find use-patterns to identify periods of occupation. Finally, the burglar would use a rogue app or script to control a door handle and invade the house. This scenario illustrates the importance of assessing whether the IoT device is susceptible to adversaries leveraging information obtained by analyzing the companion app.

B. Goal and Questions

The goal of this study is to assess whether the app-device communication is secure. We assume this communication occurs through the local network; remote communication through the cloud is out of the scope for this work. We also assume that an adversary targeting the IoT device would use either a rogue app or script to control the device without user knowledge. We propose a non-comprehensive list of questions to determine the attack surface on the apps. These questions are related to encryption, authentication, and communication, which is where vulnerabilities typically manifest.

Q1) Is the key hardcoded? A malicious developer could counterfeit messages if she has access to secret keys. Hardcoded keys are problematic as they are encoded literally in code. Intuitively, hardcoded keys could be mined by reverse-engineering the app, even when the code is obfuscated. For example, if a crypto API is used, one could find the key by monitoring the actual parameters of crypto library functions, whose names cannot be obfuscated and whose intent can be found from public documentation. In other cases, the developer may have chosen to implement a custom crypto function, but one could discover these functions by the ratio of mathematical instructions in the function body, as Caballero and colleagues did [14], and then use a similar method to mine the key.

Q2) Does the app use local communication? When the IoT app and the corresponding device are in the same network, local communication may be used. Unfortunately, local communication protocols do not enforce the same security guarantees compared to remote communication. For example, it is uncommon to check identities with HTTPS/SSL certificates in local communication. In contrast, in the scenario where local communication is forbidden (i.e., cloud relays messages to apps and devices), an attacker would have to make a bigger effort to forge HTTPS/SSL certificates of the parties involved.

Q3) Does the app send broadcast messages? Broadcast messages are frequently used in IoT setups to discover devices and to enable direct app-device communication when there is no hub/gateway in the setup. Their use, unfortunately, can put a smart home at risk. Adversaries can, for instance, sniff the response of devices to broadcast messages, which often include sensitive data such as the internal state of the device.

Q4) Does the app use any well-known protocol with vulnerabilities? Different protocols tailored to IoT deployments exist and some of these protocols are known to be vulnerable to attacks. According to Al-Fuqaha and colleagues, a total of seven application protocols are more frequently used in IoT deployments [15]. Using the Common Vulnerabilities and Exposures (CVE) database [16], we find vulnerability reports in four of these IoT protocols, namely, MQTT [17], SIP [18], UPnP [19] and SSDP [20]. Table I shows the number of reported issues and the ID of an example issue. For instance, the UPnP vulnerability CVE-2016-6255 allows remote attackers to write arbitrary files to the device file system [21]. Note that UPnP is the protocol with the largest number of reported issues.

III. FINDING AND CONFIRMING VULNERABILITIES

This section presents details of how we carried out a vulnerability assessment by analyzing the companion apps and then confirming the assessment by crafting proof-of-concept exploits for a selection of IoT devices. It describes the criterion for selecting apps to analyze [III-A], discusses the analysis used to answer the questions posed on Sections II-B and III-B and describes each exploit in detail [III-C].

A. App Selection Criterion

To select apps for this part of our study, we examined the 96 top-selling WiFi and Bluetooth devices on the Amazon website by popularity. We then restricted the resulting set to devices from the categories smart plugs, bulbs, or IR controllers that use Wi-Fi—largely for affordability and form-factor reasons and because Wi-Fi is popular and provides a potential attack surface if an attacker can execute code anywhere on the same network (e.g., via an app, malicious email, malicious device, or downloaded executable code on a computer on the same network). A total of 54 devices satisfied this criterion. From these 54 devices, we randomly selected (and purchased) 5 devices to run our analysis. Somewhat to our surprise, we found that two of the devices we selected use the same app (as they belong to the same manufacturer). Consequently, this section focuses on these four companion apps. For each of the apps, we did a detailed vulnerability analysis and then also developed exploits.

B. Vulnerability Analysis

This section details the tools we used to determine app-device protocol features that could permit remote or local attacks on the device. We analyzed each companion app with respect to the questions from Section II-B. We then identified a potential attack path in each app and confirmed the path by creating a proof-of-concept exploit. We describe the methodology used to answer the questions and their use to find an exploit.

Table I: CVE vulnerabilities in major IoT protocols.

| Protocol | # Vulnerabilities | Example |
|----------|-------------------|---------|
| MQTT     | 13                | CVE-2017-9668 |
| SIP      | 59                | CVE-2018-0352 |
| UPnP     | 346               | CVE-2016-6255 |
| SSDP     | 17                | CVE-2017-20042 |

4This ability to sniff WiFi messages depends on the distance to the router.
1) **Basic toolset functionality:** We implemented a toolset to help us do semi-automated analysis to answer the questions. We found relying on just automated analysis to be error-prone. For example, one of our tools looked for use of constant keys in calls to encryption functions. But, we found that some of the calls were not used on the communication paths between the device and the app. Thus, for all of our analysis, we used the tools as an aid to manual analysis. We also used the JAD decompiler library [22] as well as some static analysis tools [23].

**Encryption Discovery.** The encryption discovery component looks for functions in the app that likely encrypt and decrypt the data exchanged with the smart device. Those functions are the first line of attack for adversaries [24]. With those functions, one could, for example, eavesdrop on official communication and infer the layout of messages and gain access to sensitive data. The toolset uses two complementary heuristics to discover these encryption functions. The first heuristic applies to the case where developers use existing Java encryption APIs. The second heuristic covers the case where developers implement custom crypto functions instead of building on existing ones. The toolset detects these functions by computing, for every function declared in the app, the ratio between the number of arithmetic and bitwise operations over the total number of instructions. This heuristic has been previously used in prior work [14], [25], [26].

**Network Protocol Discovery.** This component extracts information about the communication protocol used between the smart device and the companion app. More precisely, it looks for calls to functions (in the app) from classes related to known communication protocols. For example, for UDP, it looks for calls to functions from java.net.DatagramSocket and, for TCP, it looks for calls to functions from java.net.Socket. This component reports a mapping from classes in the app to communication protocols (e.g., TCP, UDP, HTTP, UPnP). Note that there is no fundamental limitation that prevents our infrastructure supporting other languages and protocols.

2) **Answering the questions:** We describe below the methodology we used to answer each of the questions from Section II-B and then elaborate results.

**Q1) Is the key hardcoded?** The search for hardcoded keys initiates from the output of the encryption discovery component, which reports function likely related to encryption. When using standard encryption libraries, we are able to automate the search for secret keys by looking for javax.crypto.SecretKey, which is the class denoting a key in the Java standard API. For custom encryption, however, we manually inspect each method returned by the encryption discovery, checking if the key is present inside the method body or in usages of the method.

**Q2) Does the app use local communication?** The protocol discovery component acts as guidance for the manual analysis. Based on the function calls and protocol report, we manually analyze the classes responsible for network calls and identify whether the app uses local communication.

**Q3) Does the app send broadcast messages?** Identifying whether broadcast messages are sent from the app to the smart device is done by inspecting the classes responsible for making network calls and looking for well-known broadcast addresses, e.g., 255.255.255.255.

**Q4) Does the app use any well-known protocol with vulnerabilities?** With the protocol discovery component, we can identify transport, network, and application layer protocols used on the app. After identifying these protocols, we look for documented vulnerabilities for each protocol in the Common Vulnerabilities and Exposures (CVE) database [16].

**Results.** Table II shows the answer to these questions for the four selected apps. For each question, we used the labels *yes* or *no* to indicate a positive answer or a negative answer, and *no encryption* for the first question when the app uses no encryption. The label *yes* indicates good practice whereas the labels *no* and *no encryption* indicates a potential vulnerability or an interesting attack surface for a potential exploit.

All four apps are found to use local communication with the device and three of the apps also using broadcast communication, providing us with a potential attack surface to exploit the devices. Three out of four apps do not use any encryption to secure their communication with the device, providing us with a compelling attack vector. Only one of the selected apps (WeMo) uses an insecure version of a protocol. But WeMo also does not use any encryption, thus providing a simpler attack vector to exploit the device.

3) **Finding Vulnerable Paths:** After answering the posed questions, we proceed to locate vulnerable paths in the given app. We define a vulnerable path to be a sequence of function calls that connect a source (e.g., a function that is called from external input such as the user interface (UI)) to a sink (e.g., a network method call) that an exploit may wish to compromise. Analyzing the classes and functions in this path involved in the preparation of a message to a sink helps the security analyst generate an abstraction of the application behavior, an important step to creating an exploit.

![Figure 2: Path (simplified) from UI function to a network call.](image-url)

Figure 2 illustrates a vulnerable path for the Kasa app. To find this vulnerable path, we start by analyzing the output of our toolset, i.e., classes and functions related to encryption, authentication and network protocols. These elements are potential sources of vulnerabilities. Considering the Kasa app,
for example, we start by inspecting the classes containing usages of the UDP protocol (related to Q3). We discover that the UDPClient class declares the network-related method b, which calls datagramPacket.send(), a method from the standard Java API to send UDP packets. As the method b includes a network call, it could be flagged as a sink. Our analysis shows that this class contains usages of broadcast addresses, representing a potential attack surface. Then, we analyze backward the call chain leading to this function looking for a UI method. While doing it, we find another method present in the output of our toolset (related to Q1), TPClientUtils.encode, contains hardcoded keys that could also be exploited. We also identify the function TPUDPClient.a, responsible for building the UDP packet. This function, while not showing a vulnerability by itself, is responsible for building the UDP packet to be sent and reveals the structure of the message. Finally, we discover the calls to the UI obfuscated method c.a, which is the starting point of this path. That is possible because of the programming conventions of Android. More specifically, class c declares several (button-related) event callback methods.

C. Exploits

Based on the vulnerable paths found, we created exploits for each selected app. In the following, we describe in detail the steps we took to create each exploit. Although this work does not assume that an adversary would have physical access to the device, we used physical devices in this experiment to demonstrate our findings. The assumption we made on the adversary is that she understands Java and she is able to reverse engineer the Android application files (.apks). Also, when cryptographic functions and keys are encountered, we do not assume the adversary has enough computational power to break the key by brute force. We believe that these assumptions are similar to what a real-world attacker would deal with and similar to the assumptions made in other studies [27], [28].

1) Finding an exploit for Kasa for Mobile: TP-Link Kasa is the official app for controlling TP-Link-manufactured devices from the smart home product line Kasa [29]. The exploit we created consists of a rogue app that mimics the official TP-Link app and takes control of a TP-Link smart plug. It is worth noting that in principle, this app could run as code anywhere on the same network, e.g., running as a script instead of app. At the time of this writing, TP-Link’s smart plug was a top-seller with over 12,000 customer reviews on the Amazon website [30] showing an average rating of 4.4 out of 5 stars. We give an analysis of its companion app below.

Table II: Potential Threats to Selected Apps.

| App            | Avoid Hardcoded Keys? | Avoid Local Communication? | Avoid Broadcast Messages? | Safe Protocol? |
|----------------|------------------------|----------------------------|----------------------------|---------------|
| Kasa for Mobile | no                     | no                         | no                         | yes           |
| LIFX           | no encryption          | no                         | yes                        | yes           |
| WeMo           | no encryption          | no                         | no                         | no            |
| e-Control      | no encryption          | no                         | yes                        | yes           |

Listing 1: TP-Link Kasa encryption function.

```
public static byte[] encode(byte[] data) {
    byte seed = (byte) -85;
    for (int i = 0; i < data.length; i++) {
        data[i] = (byte) (data[i] ^ seed);
    }
    return data;
}
```

Q1) Is the key hardcoded? The Kasa app uses a custom encryption function, Caesar cipher [31], that is known to be easy to break. Listing 1 shows this function as it appears in the app. Line 2 shows the hardcoded seed to encrypt the data. Identifying the encryption function and its hardcoded seed gave us hope of replicating the function in a rogue app on the same network to control the device arbitrarily.

Q2) Does the app use local communication? By using the network discovery component and manually inspecting the code, we identified classes containing calls to UDP-related methods. After inspecting these classes, we confirmed that these methods are involved in the discovery and control of the TP-Link devices on the local network. For instance, Listing 2 exhibits the function that discovers TP-Link devices in the local network.

Listing 2: TP-Link Kasa function (simplified) used to discover devices on the local network.

```
public static final String UDP_ADDRESS="255.255.255.255";
public void discoverLocal() {
    String requestId = DiscoveryUtils.a();
    tpDiscovery.broadcastDiscovery(...,UDP_ADDRESS,...);
    ...
}
```

Q3) Does the app send broadcast messages? During our analysis, we found the Kasa app uses broadcast messages to discover and control the TP-Link devices. Line 1 from Listing 2 declares a constant variable holding a well-known broadcast IPv4 address. This variable is then used in Line 3 to discover TP-Link devices on the network.

Q4) Does the app use any well-known protocol with vulnerabilities? Our analysis did not find usage of protocols with documented vulnerabilities.

To confirm the vulnerabilities, we designed a proof-of-concept exploit. The exploit consists of a rogue app on the same network. We use both static analysis (i.e., inspection of the decompiled code) and dynamic analysis (i.e., inspection
of the network traffic). The list below shows the keys steps to create the exploit.

1) find a vulnerable path and encryption function;
2) discover the structure of exchanged messages;
3) discover what protocol is used to exchange messages;
4) implement pairing.

From one vulnerable path for the Kasa app (see Section III-B3), we obtain access to the app’s encryption function (step 1). With that function at hand, it is possible to monitor the network traffic and read the contents of messages as to understand their structure (step 2) and the IP addresses used (step 3), which are critical for replication. Recall that the Caesar cipher [31] is a symmetric (invertible) encryption function. In that case, we found that only broadcasting was used through a single address. Finally, it is necessary to replicate pairing (step 4). To our surprise, we found by inspection that a pairing process was not needed to control the device. Pairing was used to maintain the profile of users on TP-Link devices, but not for its control.

Monitoring the Network. We used the popular traffic analyzer Wireshark [32] to monitor the packets exchanged between the Kasa app and the device. As the traffic was encrypted we needed to implement a script to decrypt the monitored messages: the script uses the symmetric cipher function from Listing 1. This monitoring tool was used in two important stages: (i) during the app-device pairing process and (ii) while the app interacted with the device, e.g., turning the plug “on” and “off”. During the pairing process, we found that broadcast messages were exchanged while the app was connected to the hotspot created by the device. We also monitored the network when interacting with the device through the app’s UI. Specifically, we repeated the “Turn Off” and “Turn On” operation multiple times, observing that the contents of the network packets did not change, validating the use of a hardcoded key with a poor encryption method. We also observed the use of broadcast messages during device usage after pairing. We found that the app uses the following message to discover and obtain the current status of the device—{"system":{"get_sysinfo": {}}}. We also found that "{"system":{"set_relay_state":{"state":0}}}" was the message for turning the device off.

Based on the analysis, we created a rogue app to control a TP-Link smart plug device. Static analysis played an important role to find vulnerable paths in the app whereas dynamic analysis helped in understanding the communication protocol and the messages exchanged. Recall that, during our analysis, we noticed that the pairing process was not needed to control the device. This is a severe flaw as the user would not even be aware of an attack—the official app would still work as intended even with a rogue app controlling the device simultaneously. A video demonstrating the exploit is available from the link [33].

2) Exploiting LIFX: LIFX [33] controls smart lights manufactured by LIFX, a company specialized in smart lights [34]. The proof-of-concept exploit we developed is a script that takes control of a light bulb. To develop the script, we first started with finding answers to the four questions in Section I-B.

Q1) Is the key hardcoded? We found that no encryption or authentication is used in the LIFX app.

Q2) Does the app use local communication? The LIFX app uses UDP to communicate with the smart lights. As in the Kasa case, we used the output of the protocol discovery component to find that.

Q3) Does the app send broadcast messages? The app uses broadcast messages. Listing 3 shows the class responsible for sending these messages. Lines 5 and 6 refer to a fixed broadcast address. We also found that the broadcast IP address was identical to that present in the Kasa app. During our analysis of the apps (discussed in Section V), we noticed that this broadcast address is commonly used in an IoT setup, as it represents a special broadcast address that is used when a device needs to send a broadcast packet to the network without caring about a recipient’s address.

Q4) Does the app use any well-known protocol with vulnerabilities? During our analysis, we did not find any usages of protocols with known vulnerabilities in the LIFX app.

Listing 3: Function (simplified) used by the LIFX app showing usage of a broadcast address.

```
public final class UdpTransport ... {
    static {
        Object bn = InetAddress.getByName("255.255.255.255");
        Intrinsics.a(bn, ...);
    }
    ... ...
}
```

Figure 3: Path (simplified) from UI function to a network call. The path includes no encryption function.

The LIFX exploit consists of a script that sends UDP broadcast messages to control the device. Similarly to the Kasa exploit, we used static analysis to find a vulnerable attack vector for the app. For that, we inspected the code and discovered the UdpTransport class, responsible for creating and sending the UDP messages (related the Q2). While inspecting this class, we found that broadcast UDP messages were sent through the UdpTransport.accept method (related to Q3). Then, we analyzed the call chain backwards leading to the UI function responsible for controlling...
the state of the smart light, i.e., turning it “on” and “off”–
ColorController.setPowerState, the starting point of
this path. Figure 3 shows this path.

By monitoring the network while using the LIFX app to
turn the lights “on” and “off”, we confirmed that broadcast
messages were exchanged during communication between
the app and the device. Then, we proceeded to inspect the code
and find the structure of the messages. We started from the
network call from Figure 3 whose code is depicted in Listing 4.

It is worth noting that contrary to the Kasa app, which used a
JSON structure for the message, we could not infer the layout
of the message by monitoring the network only, as the message
was in a byte array format.

```java
class SetPower ... { ...
  void put(ByteBuffer byteBuffer) {
    final int SIZE = 6; long duration; int level;
    byteBuffer.putInt(this.duration);
    byteBuffer.putShort(this.level);
  }
}
```

Listing 4: Structure of messages used to turn LIFX devices
on and off.

To summarize, we created a proof-of-concept exploit script
to arbitrarily control LIFX smart lights. Similar to the Kasa
exploit described in Section II-C [1], we used static analysis
to find a vulnerable path and dynamic analysis to understand
the communication protocol between the LIFX app and the
smart light. To our surprise, we found that the app did not
implement pairing or encryption. Consequently, our script sends
unencrypted commands to change the state of the smart light,
e.g., turning it “on” and “off” and to change the color and
saturation of the light.

3) Exploiting WeMo: WeMo is the official app to control
Belkin devices from the product line WeMo [35], focusing
on a variety of IoT devices in the smart home segment. The
proof-of-concept exploit we developed is a script that arbitrarily
controls a smart plug. As with earlier apps, we started our
analysis by answering the four questions from Section II-B:

Q1) Is the key hardcoded? The WeMo app uses no encryption
or authentication in communication with the device.

Q2) Does the app use local communication? The WeMo app
uses the Universal Plug-and-Play (UPnP) protocol to handle
both device and service discovery on the local network, with
UDP acting as the underlying network protocol.

Q3) Does the app send broadcast messages? Using UPnP
implies that the SSDP protocol is used on the app. As the
SSDP protocol operates with a specific multicast address–
239.255.255.250– broadcast messages are not used.

Q4) Does the app use any well-known protocol with
vulnerabilities? We found that the app uses the UPnP protocol.
Although simple by design, this protocol is known to be
vulnerable. In 2013, a security company discovered that over
80 million devices were susceptible to a UPnP vulnerability
caused by excessive privilege in the network interface of those
devices [36]. They found that this vulnerability was actively
being used in distributed denial-of-service (DDoS) attacks.

The WeMo exploit consists of a script that searches for
a Belkin smart plug on the network and sends commands
for controlling it. To find an attack path, we followed a
different approach from previous exploits. As no encryption
was present, we first monitored the network to identify the
structure of the unencrypted messages. Then, by analyzing the
code responsible for producing the message, we gathered the
necessary information to build the script.

After identifying that the app uses the UPnP protocol, we
first tried to locate classes containing UPnP service names
exposed by the devices (related to Q2). These names identify
the universal device name (udn) [37]. By design, they must
start with the prefix “urn:”. We found that the WeMoDevice
class contained the names of all services related to the Belkin
IoT devices, as seen in Listing 6. This is important as these
names are part of the request sent to the device.

```java
public class WeMoDevice { ...
  AIR_PURIFIER = "urn:Belkin:device:AirPurifier:1";
  LIGHT_SWITCH = "urn:Belkin:device:lightswitch:1";
  SWITCH = "urn:Belkin:device:controller:1";
  public void setState(String state) {
    this.mState = state;
  }
}
```

Listing 6: Service names of WeMo devices complete list
was hidden for brevity.

We then inspected the parameter(s) of this method,
TargetedMessage, highlighted in Line 2. We found that the
array of bytes encapsulated on TargetedMessage objects is
partly constructed within classes encoding different operations.
For example, the class SetPower creates a message to modify
the light power whereas the class SetColor creates a message
to modify the light color. For illustration, Listing 5 shows
a fragment of the class SetPower. The layout of messages
can be inferred from the method put. (The construction of
the message header is omitted for brevity.) The sequence of
invocations to method ByteBuffer.put* reflects the order
of fields in the corresponding message. From that, we were
able to replicate the message layout in our script. We used the
same rationale to find the layout for other kinds of messages.

```java
public class WeMoDevice { ...
  AIR_PURIFIER = "urn:Belkin:device:AirPurifier:1";
  LIGHT_SWITCH = "urn:Belkin:device:lightswitch:1";
  SWITCH = "urn:Belkin:device:controller:1";
  public void setState(String state) {
    this.mState = state;
  }
}
```

Listing 5: Structure of messages used to turn LIFX devices
on and off.

We then inspected the parameter(s) of this method,
TargetedMessage, highlighted in Line 2. We found that the
array of bytes encapsulated on TargetedMessage objects is
partly constructed within classes encoding different operations.
For example, the class SetPower creates a message to modify
the light power whereas the class SetColor creates a message
to modify the light color. For illustration, Listing 5 shows
a fragment of the class SetPower. The layout of messages
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  SWITCH = "urn:Belkin:device:controller:1";
  public void setState(String state) {
    this.mState = state;
  }
}
```

Listing 6: Service names of WeMo devices complete list
was hidden for brevity.
while using the app. The response is a SOAP envelope—the type of message used in the SSDP protocol.

Listing 7: WeMo simplified response to query the current device state.

While inspecting the code looking for the method SetBinaryState, present in the WeMo response, we found the class DeviceListManager that receives as parameters the state and udn of the device and calls the function makeStateChangeRequest. Listing 8 shows a fragment of class DeviceListManager. We then analyzed backwards the call chain from method makeStateChangeRequest leading to the UI function responsible to turn the smart plug "on". The final vulnerable path was hidden for brevity.

Listing 8: Class (simplified) responsible for sending the command to change the state of a WeMo device.

To summarize, we successfully created a proof-of-concept exploit that discovers WeMo devices compatible with the SSDP protocol located on the local network and then can execute arbitrary commands on them. We found that the app uses the UPnP protocol with well documented vulnerabilities (see Table 1), but we did not end up needing to use those vulnerabilities in the exploit since the devices also have other vulnerabilities such as not using encryption.

4) Exploiting e-Control: e-Control is the app [38] responsible for controlling all devices from Broadlink—a company specialized in smart home devices and universal remote controllers. Our exploit was implemented as a script that can arbitrarily control a Broadlink InfraRed (IR) remote controller. Similar to previous exploits, we start by answering the questions of Section II-B.

Q1) Is the key hardcoded? We did not find use of encryption or authentication in the app.

Q2) Does the app use local communication? With our protocol discovery component, we found that the e-Control app uses the QUIC UDP protocol to communicate locally with Broadlink devices.

Q3) Does the app send broadcast messages? We found usage of a global broadcast address (similar to the Kasa app), implying the use of broadcast messages. The obfuscated method at Line 2 of Listing 9 shows this usage.

Q4) Does the app use any well-known protocol with vulnerabilities? We did not find usage of protocols with well-known vulnerabilities in the app.

The e-Control exploit we developed consists of a script that can send arbitrary commands to a Broadlink IR remote controller. To create the script, we used the same methodology as the LIFX exploit, using static analysis to find a vulnerable path in the app. First, we inspected the code looking for usages of the UDP protocol, where we found the obfuscated method $a$ of the class PutInDataUnit, responsible for sending the UDP packet to the broadcast message (related to Q2 and Q3). We then analyzed usages of this method. We discovered that after scanning for devices on the local network, the function $b$ of the same class was responsible for parsing the device’s response (structured as a JSON message). Listing 9 shows the class with both methods. We then analyzed backwards the call chain involving this class and found the UI call, representing the start of the vulnerable path. We choose not to show the graph illustrating the vulnerable path for brevity reasons.

Listing 9: Class (simplified) responsible for sending an UDP message through the network.

To discover the structure of the messages, we monitored the network while interacting with the e-Control app. By inspecting the JSON messages exchanged, we confirmed the structure of the message found during our static analysis. We then replicated this structure to control the device. It is worth noting that although we found the functions related to the pairing process while inspecting the code, we did not need to replicate them on our script. A Broadlink device can be controlled independently of a previous successful pairing and without alerting the user. This is a severe flaw.

D. Vulnerability Disclosure

As of the publication deadline of this paper, we have notified all manufacturers of the vulnerabilities. During disclosure, we also included scripts showing how to control the device without the official IoT app and possible approaches to mitigate the issues we found. None of them have sent any response to our disclosures and to the best of our knowledge, have not released patches relative to these vulnerabilities.

E. Threats to Validity and Limitations

The main threats to the validity of this study are the following. External Validity: We ran this study against five devices, associated with four different apps. Although we analyzed more apps (see Section IV), we only purchased these devices. As usual, the results may not generalize to
other devices. To reduce bias, we selected smart home devices according to a well-defined criterion based on popularity in the Amazon website. It is worth noting that the characteristics of the apps that control the devices we purchased are similar to the ones we analyzed but not purchased.

Internal Validity: Our results could be influenced by unintentional mistakes during human inspection. For example, we could have missed an important vulnerable path in an app.

As for limitations, our infrastructure and methodology do not account for the possibility of apps making Java Native Interface (JNI) calls. In this study, none of the apps calls native functions through JNI. In a complementary study (see Section IV), however, we found that some apps make JNI calls. They use JNI, for example, to implement encryption. As expected, reverse-engineering native code is more challenging.

IV. Discussion

This section describes findings from a larger set of apps compared to the one used in Section III that enabled us to construct exploits. In this case, we did not purchase devices, so these findings are indicative of the potential extent of vulnerabilities. IoT devices included cameras, locks, and alarms, suggesting a significant safety issue if the vulnerabilities we found were exploitable. We consider companion app analysis to be a valuable tool for discovering potential vulnerabilities prior to making purchases of large or expensive smart appliances or where human safety could be an issue. Our analysis is conservative with respect to potential vulnerabilities. We only present a negative result if we can confirm it in code. For example, by analyzing the eWeLink app, which uses native code, our analysis was not helpful in analyzing the app for hardcoded keys and, to be conservative, we counted the app as not having vulnerabilities to hardcoded keys.

For this experiment, we start with the top-100 smart hubless devices on the Amazon website by popularity and then restrict the resulting set to devices that use WiFi and Bluetooth for communication. We find 96 such devices, including the 5 devices that we previously purchased and analyzed in Section III. These 96 devices only correspond to 32 companion apps, saving us significant analysis effort compared to analysis of devices themselves.

Figure 4 shows the distribution of answers to the questions for the analyzed apps as pie charts. To answer these questions we used the same methodology described in Section III. Considering these questions, we find 31% of the apps to not use any encryption at all and 19% to use hardcoded keys, strongly suggesting that at least 50% of the apps are potentially exploitable with further protocol analysis. These correspond to 37 out of 96 devices, i.e., 38% of the devices.

Out of the 32 apps analyzed, we found 4 apps to use encryption without hardcoded keys, not use local communication, not use broadcasts, and not use known insecure protocols. All their communication was via the cloud service, likely over SSL. The four apps include the popular Nest app. With respect to attacks considered in this paper, this is a relatively secure way to communicate. But it does have a privacy tradeoff in that the cloud service has access to the commands sent to the device. Consequently, a potential long-range security risk exists if the cloud service is ever compromised, a non-negligible risk [39].

We observe that 18 apps communicate locally with their corresponding device(s) and that 16 apps use broadcasting. Note that a negative answer to a question does not imply an exploitable vulnerability. Further inspection is necessary to understand the issue. For example, although the app “August Home” uses local communication, that happens only through Bluetooth, which may restrict an attacker to be in close proximity to the device, limiting the attack surface. The app “Ring—Always Home” also does not appear problematic. After closer inspection, we find that the use of SIP, a protocol known to be insecure (see Table I) is due to one specific feature of the app, Voice over IP (VoIP). However, this feature can be disabled and, if enabled, it is isolated from other parts of the app (with no apparent flows in between).

V. Defense Strategies

Our analysis suggests that developers of software for IoT devices find it non-trivial to do proper key management. 50% of the apps either used hardcoded keys or did not do encryption. Some apps though did not use hardcoded keys and it is instructive to see how they secured app-device communication.

We have not found use of a hardcoded key or of local communication in Nest thermostat’s companion app. The Nest thermostat provides a UI interface that provides a display and also entry of data (by rotating a ring around the thermostat). A user can use that interface that to select a WiFi network and enter the WiFi password. That allows the device to talk to the Nest cloud service securely over SSL. The companion app does not talk directly to the device; instead, the user creates a free account on the Next cloud service and then signs into that using the companion app over SSL. Then, the user adds the thermostat to his account by entering a random code that is displayed on the thermostat’s interface. The user that way is assured that the correct thermostat is being added to the account. Furthermore, the thermostat and the cloud service can also mutually authenticate each other and establish a shared secure link. No shared keys between the companion app and the thermostat are required since, from then on, the communication between the companion app and the thermostat happens over SSL links to the cloud service.

The EZVIZ uses a different strategy. Unlike Nest, it supports local communication between the companion app and the device over the local network. The shared encryption key is enclosed in the box in the form of a QR code and must be scanned by the companion app. This strategy is better than hardcoded keys provided the key in the QR code is of sufficient length, random, and strong crypto library is used.

Certain strategies are not recommended. We found several apps rely on native code. In our current analysis, we did not analyze native code and thus could have missed some uses of hardcoded keys. But, it is certainly possible to analyze binary code using tools such as Ida Pro [40] and extract...
potential constants, including keys. Similarly, code obfuscation, is unlikely to be an adequate defense.

VI. RELATED WORK

In this section, we review some of the previous studies on security in a smart home context.

Denning et al. [3] presented potential security attacks against smart home devices, pointing that common attacks to traditional computing platforms, like denial-of-service and eavesdropping on network could also be used in a smart home context. Komninos et al. [41] presented a survey about smart home security, pointing different usage scenarios and categorizing threats into network domain (such as eavesdropping, traffic analysis and replay attack) and smart home introduced concept (such as device impersonation, update and illegal software).

Focusing on IoT platforms, Fernandes et al. [6] analyzed over 499 apps on SmartThings and found out that 55% of those are over-privileged largely due to design flaws in the privilege model of the platform. The authors also demonstrated how to take advantage of this with four proof-of-concept attacks, both remotely and locally. Jia et al. proposed a context-based permission system for appified IoT platforms with fine-grained context identification and runtime prompts [42]. Other works [43], [44] focus on program analysis techniques used on IoT platforms. Most of these works analyze apps written in platform-dependent and restricted languages whereas we analyze companion apps in the larger Android platform.

Android apps have been analyzed for a variety of security-related issues, such as cryptographic misuse [24], [23], [45] and memory corruption [46]. For example, Egele et al. [24] analyzed the violation of six rules including the use of ECB mode and constant keys/IVs/seeds. Wei et al. [23] designed a static analysis tool for security vetting of Android apps and used it to detect the use of the weak ECB mode for encryption; the analysis is intra-procedural and thus limited in scope.

In 2015, the Veracode team published a white paper on security analysis of six IoT devices to examine vulnerabilities involving non-use of cryptography, lack of enforcement of strong passwords, and incorrect TLS certificate validation [47]. The white paper mentions that the team used network monitoring and reverse engineering techniques, but did not discuss details of what was reverse-engineered (e.g., device firmware, apps, or cloud services) or how. Our work differs in that it focuses on a different set of vulnerabilities (e.g., many of the apps we analyzed in 2018 use cryptography, but with hardcoded keys) and we present details of analysis of companion apps to show how such vulnerabilities can be discovered.

VII. CONCLUSIONS

Securing communication between IoT devices and the mobile apps responsible for controlling them is crucial for security and even safety, depending on the types of IoT devices on a network. Unfortunately, analysis of device firmware is usually non-trivial. In this study, we showed that analyzing the smartphone companion apps that are released for the device can provide important clues for potential vulnerabilities in the devices. By analyzing the companion app code, we assessed whether the communication between five best-selling IoT devices and their companion apps occurs over a secure channel. We found that was not the case. We were successful in creating exploits for all five devices and able to control them, leveraging information that we gathered while analyzing the companion apps, both statically, through program analysis, and dynamically, through monitoring the network. We also extended our study to 28 additional apps. We found that 31% of the apps do not use any crypto to protect the device-app communication and that 19% use hardcoded keys. A significant fraction of the apps (40–60%) also use local communication or local broadcast communication, thus providing an attack path to exploit lack of crypto or use of hardcoded encryption keys.
