Phantom Device Attack: Uncovering the Security Implications of the Interactions among Devices, IoT Cloud, and Mobile Apps

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Abstract—Smart home connects tens of home devices into the Internet, running a smart algorithm in the cloud that sends remote commands to the devices. While bringing unprecedented convenience, accessibility, and efficiency, it also introduces safety hazards to users. Prior research studied smart home security from various aspects. However, we found that the complexity of the interactions among the participating entities (device, IoT cloud, and mobile app) has not yet been systematically investigated. In this work, we conducted an in-depth analysis to four widely used smart home solutions. Combining firmware reverse-engineering, network traffic interception, and black-box testing, we distill the general state transitions representing the complex interactions among the three entities. Based on the state machine, we reveal several vulnerabilities that lead to unexpected state transitions. While these minor security flaws appear to be irrelevant, we show that combining them in a surprising way poses serious security or privacy hazards to smart home users. To this end, five concrete attacks are constructed and illustrated. We also discuss the implications of the disclosed attacks in the context of business competition. Finally, we propose some general design suggestions for building a more secure smart home solution.

I. INTRODUCTION

With the development of Internet of Things (IoT), smart home technology has become more and more popular. Smart home devices can enable in-cloud application logic (e.g., IFTTT) to remotely control home environments. Due to this tangible convenience, smart home has been widely used in many applications including safety and security [24], home appliance [6] and home healthcare [8]. According to the latest statistics [11], 433.1 million smart home devices were shipped worldwide in 2017. That is a growth of 27.6% compared with 2016.

To manage the ever-increasing number of smart home devices in a unified way, many smart home solutions have been proposed and deployed. Although individual smart home solutions adopt different business models, when it comes to the general design principles, all of them are quite similar. Due to several compelling reasons, cloud-based device management (CBDM) services have become a standard and crucial part of commercial smart home solutions. First, when users are not in the same local area network with devices, they must rely on CBDM service to remotely control and monitor the devices. Second, because only the device owner has full access to the smart home devices, it is necessary for the CBDM service to take charge of the device identification and maintain a one-to-one mapping between the device owner’s account and the target device. Last but not least, CBDM service makes it convenient to trigger user-designated rules that trigger device actions. For example, if a thermometer detects that the temperature exceeds the specified threshold, the cloud service will send a command that turns on the air conditioner. In practice, CBDM services run on the cloud maintained by the smart home solution providers. In the remainder of this paper, we use CBDM and IoT cloud interchangeably. With CBDM services playing a central role in smart home solution, real-world smart home solutions essentially engage three entities that interact with each other: CBDM service (a.k.a., IoT cloud), smart home devices and a mobile app. Briefly speaking, the mobile app provides users with a user interface to facilitate the initial setup (i.e., enrollment) of devices (e.g., WiFi credential provisioning) and control/monitor the devices through IoT cloud. Device firstly uses the WiFi credential to access the Internet, and gets the credential identification from IoT cloud. Then, it keeps a heartbeat connection with IoT cloud to routinely report its statuses and execute the remote control commands.

While bringing convenience to our lives, smart home also introduces potential safety hazards. Since smart home devices directly process user generated data, once compromised, serious consequences can happen. For example, user privacy can be leaked [40], [19], [35]; money can be lost [27], [28]; sometimes it can even endanger life safety [16] or harm psychological health [33]. In the literature, security and privacy problems in smart home are investigated from three perspectives:

1) **PI: Firmware-level vulnerabilities discovery:** It has been disclosed that the firmware in many widespread smart home devices have vulnerabilities regarding authen-
Problem Statement: Studied in the literature, problematic state transitions have not been comprehensively evaluated. The security and privacy implications of the three entities could result in a variety of serious risks. The overall complexity introduced by interactions among the three entities is largely uninvestigated. Research work in P2 focuses on localized security on the device side without considering the whole interactions. Second, research work in P3 investigates privilege misuse. However, interactions among the three entities is largely uninvestigated. Third, research work in P3 focuses on one particular protocol at a particular stage, e.g., the Bluetooth Low Energy (BLE) protocol between wearable fitness trackers and mobile app. As a result, due to a focus on localized analysis, the overall complexity introduced by the interactions among the three entities is largely uninvestigated. Third, research work in P3 investigates privilege misuse. However, with a focus on the risks of over-privilege problem, they leave the risks of unexpected state transitions largely uninvestigated. The overall complexity introduced by the interactions among the three entities would unavoidably result in a variety of state transitions. The security and privacy implications of problematic state transitions have not been comprehensively studied in the literature.

Key Observation: Although these three perspectives provide researchers with essential understanding about several concrete cyber-attack scenarios, we found that the complexity of the interactions among the three entities has not yet been systematically investigated. Our key observation has at least three aspects. First, the major findings of research in P1 only apply to firmware of specific devices. The revealed vulnerabilities have little to do with the interactions among the three entities mentioned above. In particular, they only focus on the local security on the device side without considering the whole interactions. Second, research work in P2 focuses on one particular protocol at a particular stage, e.g., the Bluetooth Low Energy (BLE) protocol between wearable fitness trackers and mobile app. As a result, due to a focus on localized analysis, the overall complexity introduced by the interactions among the three entities is largely uninvestigated. Third, research work in P3 investigates privilege misuse. However, with a focus on the risks of over-privilege problem, they leave the risks of unexpected state transitions largely uninvestigated. The overall complexity introduced by the interactions among the three entities would unavoidably result in a variety of state transitions. The security and privacy implications of problematic state transitions have not been comprehensively studied in the literature.

Problem Statement: Based on the key observations, our research hypotheses are that (a) regarding the security and privacy hazards in smart homes, the findings in existing literature are not really comprehensive; more serious hazards should exist, although not yet reported in the literature; (b) from the new perspective of unexpected state transitions (involved in the interactions among the three entities) and the new perspective of integrated analysis, more serious hazards could be discovered.

Research Questions: In particular, our main research questions are as follows: Question 1: Could we distill the general state transitions representing the interactions among the three entities? Could we identify the unexpected state transitions caused by the complexity introduced by the interactions among the three entities? Question 2: Do the unexpected state transitions, if any, pose a security or privacy hazard? Question 3: When several minor security flaws appear to be irrelevant, could they be combined in a surprising way to abuse certain state transitions and construct serious attacks?

To answer these research questions, we conducted the following investigations. First, because all the communication among the three entities is encrypted, we combined many techniques including firmware reverse-engineering and man-in-the-middle monitoring (to break SSL) to figure out the detail of the interactions among the three entities. Second, based on the work-flow and interactions among the three entities, we drew three general state transition diagrams corresponding to the three entities and identified unexpected state transitions in several commercial smart home solutions. To confirm and trigger unexpected state transitions, we implemented a phantom device that mimics a real device. A phantom device is essentially a software program. Third, we also manually reviewed the code of device-side and mobile-side SDK, and used black-box testing to investigate the CBDM service to find other security flaws. Finally, to exploit the disclosed vulnerabilities, we also leveraged a phantom device to impersonate a real device that intervenes in the normal interaction of legitimate smart home devices, leading to unexpected state transitions.

In summary, the main contributions are as follows:

New Insights are Developed: (a) CBDM service does not strictly guard the validity of the state transitions. We found that the CBDM service can accept some device requests without checking whether it should be allowed or not in present state. (b) The three entities do not strictly obey their state machines and the three entities could be out of sync. (c) CBDM service does not perform sufficient authorization check for device-side requests. We found that CBDM service simply accepts and executes authorized sensitive commands without any permission checking. (d) Ingeniously using a combination of irrelevant flaws mentioned in the first three insights, we show that serious new hazards can happen. This new finding proves that high risk attacks are rarely caused by a single factor. We should conduct integrated analysis on security flaws identified from different aspects of a smart home solution.
New Hazards are Discovered: (a) An adversary can remotely take over a device. As a result, he can harvest the sensor output to monitor the victim’s home or even manipulate the smart home devices, causing privacy breach and endangering the victim. (b) An adversary can stealthily remotely replace a real device with a non-existing phantom device under control. As a result, all the control commands from the victim user are exposed to the phantom device and further to the adversary, leading to privacy leakage. The adversary can also leverage the phantom device to manipulate the data to be sent to the victim, thus deceiving or misleading the victim. (c) An adversary can utilize the phantom device to automatically send update requests to the cloud to steal the various proprietary firmware in large-scale. (d) An adversary can leverage a phantom device to mislead the cloud and occupy the identity of a real device before sale. When a consumer buys such a device, he cannot bind this devices with his account.

The newly discovered hazards have significantly enlarged the known attack surface of smart home solutions; they also provide essential new understandings about the security and privacy hazards in smart homes.

POC Attacks are Implemented: For each hazard, we have developed a POC attack. We have successfully launched these POC attacks to a load of different kinds of smart home devices from several vendors. These devices include smart plug, IP camera, WiFi bulb, cleaning robot, and smart gateway, etc. The tested devices in this work are shown in Figure 1. To visually demonstrate our representative attacks, we recorded 2 videos. [11]

Responsible Disclosure. All vulnerabilities described in this paper have been reported to the corresponding vendors, who have confirmed our disclosures. We have also shared the technical details and most of the reported vulnerabilities have been fixed.

II. INTERACTIONS AMONG DEVICES, IoT CLOUD AND MOBILE APPS

A. Smart Home Solutions: Developer’s View

Figure 2 shows the developer’s view of a smart home solution. Corresponding to the three entities, a smart home solution provides three key components as shown in Figure 2. First, the device-side SDK contains common communication functions and protocols that enable the IoT device to interact with the IoT cloud and the mobile app. Second, the mobile-side SDK contains communication functions and protocols that enable the mobile app to interact with the IoT cloud and the device, and provide several interfaces for a user to use the device. Third, the IoT cloud consists of device management logic (e.g., device identification and authentication), a database to store device information and user accounts, remote command transfer, and smart user-designated logic (e.g., IFTTT).

It is clear that the aforementioned smart home solution could benefit software developers and device vendors a lot. The adopting device manufacturers only need to focus on the device-specific boot-up code and simply enable their firmware to invoke the device-side SDK to interact with IoT cloud and mobile apps.

B. Interaction Model

In this section, we describe interaction model of a typical smart home. Before the device can be remotely controlled and monitored by the authorized user, there are several steps to setup the device.

1) Device Discovery: After the user has installed the official mobile app of the IoT device, he registers an account in the cloud and logs in the mobile app. Then he scans the QR code on the device label using the mobile app or manually selects the target device model name listed in the mobile app. The app will then broadcast the discovery message. The target device responds by reporting to the app the basic device information such as MAC address, device model, and firmware version.

2) WiFi Provisioning: To access the Internet, IoT devices need to obtain the WiFi credential from mobile app. This can be achieved by several mechanisms, including Access Point Mode [10], WiFi direct [5] and SmartConfig [20].

3) Device Registration: To manage the devices, the IoT cloud identifies a legitimate IoT device by a unique device ID. This device ID is typically provided as follows. After the device has access to Internet, it sends its unique information (e.g., MAC address, serial number) and some legitimacy credential (e.g., embedded secret) to the cloud. The IoT cloud verifies the legitimacy and generates a device ID, which is returned to the device and written to the device persistent storage. The cloud also keeps the device ID for future authentication. Note that for some smart home solution companies, the device ID is...
generated by the cloud beforehand and hard-coded into the device during fabrication.

4) Device Binding: The IoT cloud binds the device ID with the user account. As a result, only the authorized user can access the device via the cloud. If other users request to bind the same device again, the cloud will refuse this request unless the device has already been unbound.

5) Device Login: The device uses the device ID to login the cloud. The cloud then marks the device as online. The device and the cloud also maintain a heartbeat connection to keep the device status updated.

We note that the order of steps (1) and (2) are exchangeable depending on the concrete solution implementation.

When device setup is finished, four types of communication channels enable the normal work among the device, CBDM service and mobile app. These channels serve for either device control or data transmission, and operate under crypto depending on the concrete solution implementation.

1) Remote Control: When the user’s smartphone can access the Internet, it can remotely monitor and control his device via IoT cloud. Specifically, the mobile app sends control commands identified by device ID to the IoT cloud. Then the IoT cloud checks whether the user is authorized to access this device. If the checking is passed, the cloud forwards the command to the target device.

2) Local Control: When the user is in the same LAN with the device, he can directly send local control commands to the target device.

3) Smart Control: The IoT cloud can automatically send control commands to the device when user-specified rules are satisfied. For example, the user can edit a rule that turns on the smart plug at a specified time if the temperature is below 70°F. The rule is synchronized to the cloud. When the time comes and thermometer indicates that the temperature is below 70°F, the cloud will automatically send a “turn on” command to the smart plug.

4) Data Uploading: The smart home devices routinely report their statuses to the IoT cloud so that the user can monitor the latest device status remotely.

All of these interaction functions including setup and normal work are implemented by the corresponding SDKs shown in Figure 2 When the user does not want to use the device anymore, he can unbind it by sending an unbinding request to the IoT cloud. The IoT cloud will revoke the binding relationship between the device and the user account.

C. State Transitions Involved in the Interactions: A First Glance

To better understand the complexity of the state transitions involved in the interactions among the three entities, we first distill the legitimate high-level machine for these entities.

State Machine for IoT Cloud. In the state machine for IoT cloud, each node represents a working status of the IoT cloud. An activity of user’s mobile app or the device causes a state transition, which is represented as an edge. In Figure 3a, states are defined as follows. State 1: In the initial state, the user and device have no operations. State 2: The cloud generates a unique device ID for the registering device and records it in its database. Then cloud returns it to the registering device. If same device applies for registering again, the cloud directly returns the same device ID. State 3: The cloud binds the device ID with the user and maintains this binding relationship. State 4: The cloud handles the user’s requests and syncs the device status.

State Machine for Devices. Similarly, in the state machine for devices, an activity of user’s mobile app or the cloud causes a state transition (Figure 3b). State 1: The device is in the factory mode, which means it has not been used by any users. State 2: The device sends its basic information to mobile app and gets WiFi credential from app. State 3: The device received the device ID from the cloud and stores it locally. Then device tries to logs in the cloud. State 4: After cloud accepts the login request, the device keeps a connection with cloud and waits for new commands from cloud.

State Machine for Mobile App. Similarly, in the state machine for mobile app, an activity of the device or the cloud causes a state transition (Figure 3c). State 1: After the
user clicks the “Add Device” button on mobile app, the app broadcasts a message to search for available IoT device. State 2: Mobile app sends WiFi credential to the target device. State 3: The user clicks the “Bind Device” button on mobile app, then app sends a request to the cloud to bind user account with the target device. After the cloud binds the target device, a device control interface appears on the mobile app. State 4: After device logs into the IoT cloud, the user can use it to control and monitor the target device.

**State Synchronization.** Three entities state machines are closely related to each other. During interactions among these entities, their state machines should keep in sync with each other. For instance, when the device works in state 4, the IoT cloud and mobile app should also work in their state 4. If the device disconnects with IoT cloud, three entities should go back to their state 3 at the same time.

Although the state machines are quite intuitive, we found that real-world smart home solutions do not strictly implement these state machines. As a consequence, (a) we found the existence of unexpected hidden states in some real-world smart home software implementations; (b) we also found that some implementations do not check whether a requested state transition should be allowed; (c) we also found that these state machines are not always in sync with each other. In short, due to the lack of state transition protection and the complex interactions among the three entities, smart home solution providers do not really enforce a state machine for the three entities.

**D. Scope of Empirical Vulnerability Analysis**

The real-world smart home solutions can be classified into two categories depending on their functionality. The first category is dedicated for use with smart home solutions, while the second category is general IoT solutions but customized for smart home usage, e.g., Amazon Web Services (AWS) IoT [7] and IBM Watson IoT [19]. Since general IoT solutions have to be flexible to meet broad requirements, they usually have a quite different interaction model among the three entities. For example, AWS IoT uses MQTT protocol extensively which is absent in most smart home specific solutions. Due to this reason, we have to leave them out of the scope in this paper.

In this work, we performed an in-depth empirical vulnerability analysis of popular smart home specific solutions. We chose four leading smart home solutions – TP-LINK’s KASA [37], XiaoMi’s MIJIA [41], Alibaba’s (or Ali for short) Alink [3], and JD’s Joylink [22]. In the North America and Europe market, TP-LINK’s smart home devices such as smart WiFi plug and smart LED bulb rank top 10 in the category of home improvement on Amazon [11]. In addition, smart WiFi plug is the best seller in the category of Smart Plugs on Amazon. XiaoMi is the world’s largest intelligent IoT devices manufacturer. There have been more than 85 million smart home devices sold under the brand of XiaoMi all over the world [25]. Their products receive great popularity in Asia-Pacific [39]. Although there is no publicly available statistic regarding the user base of KASA and MIJIA solutions, we observe that there has been more than one million installations of their official smart home apps in Google’s play store as of July 2018.

Different from TP-LINK and XiaoMi, which closely control the software ecosystem and fabrication of their smart home devices, Ali and JD open their smart home solutions (Alink and Joylink respectively) to the public. Collaborative manufacturers get SDKs from Ali and JD, and assemble smart homes devices that enjoy IoT cloud services provided by Ali and JD. This business model powers more than one thousand IoT device models, manufactured by over 200 famous devices manufacturers including Philips, ECOVACS, and Media [4], [21]. In the remainder of this paper, we refer to devices adopting solutions backed by Ali and JD as Alink and Joylink devices respectively, because Ali and JD do not manufacture devices themselves. For the companies that fabricate their own devices such as XiaoMi and TP-LINK, we directly refer to their devices as XiaoMi and TP-LINK devices respectively.

**III. PHANTOM DEVICE ATTACK: AN OVERVIEW**

**A. Threat Model**

In contrast to traditional network-based or firmware-based exploits (e.g., buffer overflow, man-in-the-middle (MITM)), we mainly focus on the design flaws in interactions among the three entities in smart home solutions. In particular, we systematically discover and exploit common design flaws caused by the complexity introduced by the interactions among the three entities.

Due to the complexity introduced by the interactions, these security-related design flaws are more difficult to amend, and sometimes lead to severe consequences (e.g., device hijacking, data breach, etc.). More importantly, in many attacks disclosed in this paper, an attacker can put user data in jeopardy without many preconditions, making the attack extremely easy to launch. Specifically, attackers do not need to have the following capabilities.

**LAN Access.** In most of the vulnerabilities we found, the attackers do not have to be in the same local area network with the victim device. He can carry out attacks remotely.

**Exploiting Buggy Software.** The manufacturer could potentially reinforce the security of software stack by rigorous manual review or formal verification. Therefore, it might be difficult to find a security bug in any of the software behind the whole smart home platform, including the firmware on the device, mobile app, and cloud services.

**Luring the User to Install Malicious Apps.** The attacker does not rely on drive-by-download attacks to install a malicious repackaged mobile app on victim’s smartphone.

**Network Traffic Manipulation.** The attacker does not rely on a fake WiFi access point to eavesdrop network traffic among the device, mobile app, and the IoT cloud, nor can he manipulate the communication messages arbitrarily. The smart home solutions usually employ HTTPS or other crypto mechanisms to protect their communication.
We do assume that the attacker has some knowledge about the smart home solution. This knowledge is either publicly available or can be easily obtained by offline analysis.

Assumptions. (a) We assume that the adversary is aware of the detailed interactions among the three entities. The adversary can get this knowledge by reading public smart home solution documents [22, 3] and other methods mentioned in Section III-B1 (b) Because our attacks need to use phantom devices to imitate real victim devices to interact with the IoT cloud and mobile app, we assume that the adversary has some concrete information about the victim devices to mimic their behaviors. To this end, the adversary can buy the same kind of target device and physically extract same information (e.g., device model, device chip id). However, some information such as MAC address is different from device to device. We assume that the adversary can guess or brute-force attack this information. In fact, a manufacturer often allocates a block of consecutive MAC addresses to the same kind of product. To be specific, the first 3 bytes in a MAC identifies a manufacturer. The information can be queried on the Internet [23]. Thus, the adversary can fix these bytes and mutated the last 3 bytes. He has a huge chance to find a real device. For example, we bought 2 smart plugs of the same model. Their MACs are “3C:2C:94:0B:56:69” and “3C:2C:94:0B:AB:25”. We only need 21,692 mutations of the first MAC to reach the second MAC. In practice, an adversary can easily reach a random victim device in seconds because manufacturers allocate consecutive MAC addresses to the same model.

B. Analysis Methodology

As mentioned earlier, our attacks leverage design flaws in the interactions among three entities of a smart home solution. This section elaborates the methodology we used to reveal and analyze interactions among the three entities.

1) Deciphering the Interactions among the Three Entities: To protect user privacy, smart home solutions usually encrypt all the communication among the device, mobile app, and the IoT cloud. To figure out the logic of the interactions among participating entities, we need to first decipher the encrypted network traffic.

Device-Cloud and Device-App Communication. To attract more cooperative manufacturers, some smart home solution providers such as JD and Ali make their home-made communication protocols public and even open source the corresponding device-side SDK. Therefore, we can study these public documents and review the source code of the SDK to understand the interactions that involve the device without decrypting the traffic.

For companies using proprietary solutions (e.g., XiaoMi and TP-LINK), we cannot learn the protocols from public documents or source code. Thus, we have to first get the plaintext traffic. (a) For device-app communication, we analyzed the APK file of mobile app and found these devices use symmetric encryption algorithm to encrypt communication. Thus, we can easily extract the communication key or its generation method by analyzing the APK file. (b) For device-cloud communication, we found devices usually use the SSL protocol from captured packets. Therefore, we have to perform static analysis on the device firmware, and then manipulated the firmware to bypass the cloud (server) certificate validation. Concretely, we first bought some best-selling devices offered by these companies and obtained the device firmware by dumping the flash chip physically [6]. Through firmware reverse-engineering [6], we followed the data and control flow of the cryptographic functions, and were able to locate identified the hard-coded CA certificates in firmware and replaced them with fake certificates. However, we found that the devices enforce firmware integrity verification, which denies executing a manipulated firmware. To circumvent integrity verification, we further analyzed the code for integrity verification and found that most devices only use the cyclic redundancy check (CRC) algorithm, which does not depend on any secret. We easily updated the CRC values matching the manipulated firmware and successfully booted the firmware with our fake certificates. Finally, we were able to launch the MITM attack to decrypt the communication.

Cloud-App Communication. Unlike device-oriented communication, the communication between mobile apps and the IoT cloud in all smart home solutions is completely opaque to customers and us. A simple network sniffer confirmed that most solutions adopt HTTPS, and mobile apps correctly verify the validity of the cloud (server) certificate. To launch MITM attack, we must replace the cloud certificate with one controlled by us. Unfortunately, we found that mobile apps usually hard-code their own trusted certificates in the APK without relying on the trust store on the device [29] (a.k.a. certificate pinning). If we replace the hard-coded certificates, the apps deny executing due to integrity checking. We addressed this problem by rooting our test smartphone and installing an Xposed module [7]. This Xposed module is able to hook the certificate checking functions so that we can dynamically manipulate the certificate without compromising the app integrity.

2) Understanding the Interactions among Three Entities: Using the aforementioned approaches, we were able to reveal plain-text network traffic among the IoT device, mobile app, and the cloud. This greatly simplified our analysis. Although different solutions adopt different protocols, it is a common practice that these messages are encoded using the JSON format, which is quite self-explanatory. Thus, we could understand the function of each interaction message. For instance, we show a message sent from a device to the cloud in the Alink solution in Listing 1. As indicated by the method field, this message is used to register the device. In addition, Listing 1 also shows that the device needs to send device legitimacy credential (e.g., sign, key) and identity information (e.g.,

https://www.youtube.com/watch?v=KlV3_HaBpbs
https://www.iotpentestingguide.com/firmware-hacking.html
https://github.com/Fuzion24/JustTrustMe
cid, sn, model, mac) to the cloud to get registered. Then, to figure out the complete interactions among three entities, we manually triggered most of the normal functions from both the mobile app (e.g., sending a control message) and the device (e.g., pressing the physical reset button), and were able to capture the corresponding JSON messages. Finally, we could detail the interactions among three entities and distill the general state transition diagrams shown in Figure 3.

```json
{
  "system": {
    "cid": "000000000000000010671484",
    "request": {
      "key": "5gPFl8G4GyFZ1fPWk20m",
      "time": "",
      "sign": "3a07945eb6f453e6c0a4032c184c87",
      "jsonrpc": "2.0",
      "lang": "en",
      "params": {
        "system": {
          "message": "messages from the cloud corresponding to different inputs"
        }
      }
    },
    "key": "5gPFl8G4GyFZ1fPWk20m",
    "time": "",
    "sign": "3a07945eb6f453e6c0a4032c184c87",
    "jsonrpc": "2.0",
    "lang": "en",
    "params": {
      "system": {
        "message": "messages from the cloud corresponding to different inputs"
      }
    }
  }
}
```

Listing 1: JSON Representation of Alink Device Registration Message

3) Vulnerability Analysis: To further identify security flaws, we investigated whether basic security properties are properly implemented. We are curious in the following questions classified in three classes.

1) Authentication Management: Which information is involved in the generation of device ID? How does the IoT cloud enforce device legitimacy checking? Can different devices be registered under the same device ID?

2) Authorization Management: Do IoT cloud and device properly perform any privilege checking based on the authorization information?

3) State Transitions Checking: Do the three entities strictly follow the state transitions defined in Section II.C.

Since we cannot arbitrarily change the requests of a real device, we ran a software agent that mimics a real device to assist our analysis. We call it a phantom device in this paper. We leverage a phantom device for both reverse engineering and constructing real attacks. A phantom device is constructed as follows. Some smart home solution providers like JD/Ali open-source their device-side SDKs and demo programs, which include the same communication logic as a real product. We simply reused them to build our phantom device. On the other hand, XiaoMi and TP-LINK use proprietary SDKs. We had to reverse-engineer the firmware we obtained from real devices, and implemented programs to imitate communication functions.

Authentication Management. The IoT cloud takes charge of device identity management. However, the logic implemented in the IoT cloud is a black box for us. In order to answer the question about device ID management, we examined return messages from the cloud corresponding to different inputs from the phantom device. By adjusting the device-side input parameters, we were able to figure out the relationship between the input parameters and cloud-side responses, which discloses cloud-side logic.

In the following, we give a concrete example of how we found and confirmed the factors that affect the generation of a device ID in the Alink solution.

```
{
  "system": {
    "cid": "0800000000000010671484",
    "params": {
      "model": "JIKONG_LIVING_OUTLET_00003",
      "mac": "60:01:94:A2:D5:7C",
      "version": "0.0.0;APP2.0;OTA1"
    }
  },
  "key": "5gPFl8G4GyFZ1fPWk20m",
  "time": "",
  "sign": "3a07945eb6f453e6c0a4032c184c87",
  "jsonrpc": "2.0",
  "lang": "en",
  "params": {
    "system": {
      "message": "messages from the cloud corresponding to different inputs"
    }
  }
}
```

Listing 2: JSON Representation of Cloud-side Response to Alink Device Registration Message

The format of the message provisioning device ID from IoT cloud is shown in Listing 2 with uuid being the device ID. First, we changed the value of each field (e.g., model, mac, cid and version) one by one, sent these artificial messages through the phantom device, and recorded the responses from the cloud. Second, we kept the device registration message fixed but sent the requests using different IP addresses, and then recorded the corresponding responses. Thirdly, we also kept the device registration message fixed but sent the requests at different times, and then recorded the corresponding responses. Finally, we compared the received device IDs to infer which factors influence the generation of device ID. In conclusion, we found that the fields model, mac and cid uniquely determine a device ID and no timestamp is involved. In other words, there is a one-to-one mapping between (model, mac, and cid) tuples and device IDs for Alink devices. We also use a similar method to infer which factors are used for device legitimacy checking.

Authorization Management. After users has bound the target device, we checked whether IoT cloud and device properly perform privilege checking for device-side and mobile-side commands, respectively. To be specific, we sent and recorded all device-side requests to cloud. Then we checked whether the requests contain any information about user account. If so, we changed the authorized user account information with an unauthorized user account or directly removed user account information in the requests. Finally, we sent these modified requests through a phantom device to the IoT cloud and observed whether the IoT cloud accepts these requests or not. Based on the same method, we also checked whether the device can accept the mobile-side commands without authorization checking.

State Transitions Checking. We tested state transitions from two aspects. First, we tested whether each entity strictly maintains its own state machine. For example, as shown in Figure 3a, when IoT cloud operates in state 2, we used the phantom device to trigger a state transition 4, which should be denied. We then observed whether this transition is executed or not. Second, we tested whether the three state machines (see
TABLE I: Design flaws in different solutions

| Design Flaw                          | Alink* | Joylink† | MIJIA | KASA |
|--------------------------------------|--------|----------|-------|------|
| F1: Insufficient Legitimacy Checking | ✓      | ✓        | ✓     | ✓    |
| F2: States Out of Sync               | ✓      | ✓        | ✓     | ✓    |
| F3: Insufficient States Guard        | ✓      | ✓        | ✓     | ✓    |
| F4: Unauthorized Device Unbinding    | ✓      | ✓        | ✓     | ✓    |
| F5: Unauthorized Local Command       |        |          | ✓     | ✓    |

*: Alink devices do not support local commands.
†: Device-side SDK of the Joylink solution does not support unbinding command.

TABLE II: The relationship between flaws and attack consequences

| Smart Home Solution | Exploited Design Flaws | Attack Consequences |
|---------------------|------------------------|---------------------|
| Alink Solution      | F1, F2, F3, F4         | Remote Device Hijacking |
|                     | F1, F3                 | Local Device Hijacking |
| Joylink Solution    | F1, F3                 | Remote Device Substitution |
| MIJIA Solutions     | F1, F2, F3, F4         | Remote Device Substitution |
|                     | F1, F3                 | Local Device Hijacking |
| KASA Solution       | F1, F2, F3, F4         | Remote Device Substitution |
|                     | F1, F3                 | Local Device Hijacking |

Figure 3 are always in sync with each other. For example, when the IoT cloud operates in state 4, the real device and mobile app should also work in state 4 in their state machines, respectively.

C. Identified Design Flaws

We have discovered five design flaws from three aspects. Most of these flaws are shared among major smart home solutions. We summarize them in Table I.

1) Weak Device Authentication: Although existing smart home solutions employ certain device authentication mechanisms, we found them insufficient.

F1: Insufficient Legitimacy Checking. Smart home solutions usually use pre-configured information to identify legitimacy devices, but not precisely matched with unique device information and can be easily obtained. For example, some smart home solutions like Alink allow the same credential to be used in multiple devices. Thus, an attacker can fix the credential and mutate the MAC address, device model, etc. to emulate different devices. Specifically, an attacker is able to steal one credential and then configure a phantom device with fixed credential and any the MAC address, device model, etc. to get registered from cloud. The cloud is then fooled to believe that a new legitimate device is connected as shown in Figure 4F1. In certain circumstances, the attacker is even capable of controlling the emulated device identity as the target device, leading to targeted attacks.

2) Loose State Transitions Checking: Through our experiments mentioned in Section III-B3, we found that three entities state machines are not well maintained by smart home solutions.

F2: States Out of Sync. As shown in Figure 3, ideally, if the user does not want to use the target device, he might turn off the target device (5) which makes the IoT cloud go back to state 3, and then unbinds the device. At same time, because cloud loses connection with the device, the device also goes back to state 3. However, we found if the user does not turn off the target device before unbinds it, the IoT cloud does not terminate the connection with the device, but accepts user’s unbinding request, which makes the IoT cloud go to an unexpected state 5 as shown in Figure 3. We used MITM proxy to confirm that connection between the IoT cloud and device is still maintained even if the device is unbound. Worse still, because the cloud does not disconnect with the device, the device is still in its state 4 (Figure 3B), thus it is still able to respond to the IoT cloud on the maintained connection. At this moment, three entities are out of sync. We call this device a dangling device (Figure 4F2). In Section IV we show how we leverage a dangling device to hijack a remote device.

F3: Insufficient States Guard. As shown in Figure 3 when IoT cloud works in state 4, the real device is also normally work in synchronous state 4. Ideally, the IoT cloud should only accept status upload requests from target device. However, the IoT cloud can accept some device requests (e.g., device registration, device login) which should not appear in this state from target device. This allows a remote attacker to build a phantom device that has the same device registration information as a target device and send register request to cloud. Even though real device has been in use (state 4), the cloud is fooled to send back the same device ID as the real device to the phantom device (Figure 4F3).

3) Weak Device Authorization Checking: By vulnerability analysis, we found the device authorization check in many smart home solutions is incomplete.

F4: Unauthorized Device Unbinding. As mentioned earlier, the IoT cloud maintains the binding relationships between user accounts and target devices. In particular, the IoT cloud only forwards commands to IoT devices that the user is authorized to access (i.e., bound devices). However, we found that IoT cloud only strictly carries out authorization checking to mobile-side commands and ignores some device-side commands. For instance, to bind a device to another user account, the existing binding information must be revoked first. Normally, the user sends the unbinding command using the UI function on the mobile app. The IoT cloud only executes the command if this command is sent from the authorized user. Unfortunately, in many smart home solutions, device unbinding can also be achieved without using the mobile app. Specifically, a device-side SDK usually includes an interface that sends unbinding commands. Note that the IoT cloud trusts the connection with the device. Therefore, it simply executes the command sent from the device without any authorization checking (Figure 4F4). As a consequence, an attacker can build a phantom device to forge an unbinding request using this device-side API. The binding information of the victim device is then revoked without user awareness.

F5: Unauthorized Local Command. LAN mistrust flaw has
Device Legitimacy Checking. In Section II-B, we have mentioned the importance of device ID, which uniquely identifies a device. Recall that the cloud needs to check the legitimacy of a device before generating a device ID for it. In the Alink solution, the legitimacy credential is a 2-tuple consisting of a key and a secret. The Ali cloud only accepts the registration requests from a device having a legitimate credential. However, it does not check other device information such as device model and serial number. Moreover, the same legitimate credential can be used by multiple devices simultaneously. In other words, an attacker can connect multiple different models of devices with the same legitimacy credential to the cloud (F1). Even worse, we found that obtaining a legitimate credential is extremely easy — a bunch of such credentials are available on the official Github repos of both the Ali company\(^7\) and corporate manufacturers\(^8\).

Device ID Generation Rules. A device is ultimately identified by its device ID — a universally unique identifier (uuid) in the case of Alink. Based on our study, the value of uuid depends solely on device identity information consisting of a 3-tuple of MAC address, device model and Device Chip ID

https://github.com/alibaba/AliOS-Things
https://github.com/espressif/esp8266-alink-v1.0
Trudy can register a new device which has the same uuid due to F3. The cloud is then fooled to register two devices simultaneously with the same uuid, with one of them being a phantom device controlled by the attacker.

B. Prerequisites and Feasibility Analysis

The first step in our remote device hijacking attack is to build a phantom device having the same device ID (uuid) as the victim device. Based on the aforementioned device legitimacy checking and device ID generation rules, the attacker needs to obtain a legitimate credential which is available online, and the victim device’s identity information (i.e., MAC address, device model, and CID).

We now analyze the likelihood of obtaining victim device’s identity information. First, the device model and CID are fixed for a specific device type. Therefore, an attacker can extract them from any real device of the same type. For example, he can read the corresponding device model displayed on the mobile app. For MAC address, the attacker can easily guess or brute-force attack this information, because a manufacturer usually allocates a block of consecutive MAC addresses to the same kind of products as we mentioned in Section III-A.

C. Attack Details

We now detail how we leverage a phantom device to remotely hijack a victim device. The top of Figure 6 shows the regular workflow of how a legitimate users Alice use the real device. Due to limited space, we only abstract key processes without listing concrete parameters. Appendix A gives a complete sequence diagram. After the legitimate user Alice provisions the device with WiFi credential (Step A.1), the device sends its legitimacy credential and device identity information to the cloud to get registered (Step A.2). Based on the device identity information, the cloud registers the device with a device ID A and binds it with the legitimate user account Alice (Step A.3). After the device logs in, Alice can control the device with her account.

Then, the attacker Trudy kicks in as shown at the bottom of the figure. With an arbitrary legitimacy credential obtained on the Internet and guessed device identity information, she can send the same device registration request to the cloud as in step A.2 (Step T.1). Due to F3, the cloud accepts this request and registers both real and phantom device with the same device ID A, but still keeps device ID A bound with Alice. At this moment, Alice actually binds the phantom device and real device at the same time. Due to F4, now Trudy logs in the phantom device and sends the device-side unbinding request to the cloud (Step T.2), which puts the real device in the dangling status (due to F2). Finally, Trudy binds the device with her own user account (Step T.3) and completely hijacks the real device (Step T.4).

D. Attack Impact

The remote device hijacking attack allows the attacker to bind his account to the victim device. As a result, he can harvest the sensor output to monitor the victim’s home or even manipulate the smart home devices (e.g., remotely turning on the IP camera), causing privacy breach and endangering the victim.

In theory, this attack is applicable to all the devices models across solutions, except that the prerequisites differ slightly from each other. In our experiments, we have verified the effectiveness of our attack on not only Alink devices (RIWYTH mobile remote HD monitor with model RW-821S-ALY 2.3.3, Philips WiFi power adapter with model SPS9011A/93), but also TP-LINK devices (smart WiFi plug with model HS100, smart WiFi LED bulb with Model LB110) and XiaoMi devices (smart home multi-functional gateway alarm system).

E. Stealthiness Analysis

It is evident that our attack is not observable from the victim during attack setup. However, after successfully hijacking the device, the victim cannot talk to his IoT device anymore, which could raise alert for security-savvy users. For ordinary users, they may simply regard it as a service failure and rebind their user accounts. It is also worth mentioning that even for security-savvy users, they cannot trace back to the attackers, because the local device does not store any information about the remote attacker.

V. CASE STUDY: REMOTE DEVICE SUBSTITUTION

We follow the flow of Section IV to describe the proposed remote device substitution attack. Different from the previous hijacking attack, in the remote device substitution attack, the attacker can remotely and stealthily replace a victim device with a phantom device under control only by leveraging the combination of flaws F1 and F3. By manipulating the status of the phantom device, the attacker can feed arbitrary inputs
to the legitimate user’s mobile app and the cloud. He can also capture all the control commands issued from the victim user, causing privacy breach. In this section, we showcase a concrete attack to the TP-LINK devices.

A. KASA Solution Specifics

As with the previous attack, the premise for our device substitution attack is device ID, which is called deviceId in the case of TP-LINK devices. Unlike other solutions, the device IDs are generated by the cloud beforehand and hard-coded in TP-LINK devices. The cloud also binds each device ID with a unique 2-tuple information consisted of a MAC address and a hardware id hwid. Device legitimacy checking is actually implemented by checking the matching between the device ID and the mac/hwid tuple.

B. Prerequisites and Feasibility Analysis

Because of the legitimacy checking, an effective phantom device must have the same device ID, hwid, and MAC address with the victim device. The long enough device ID (20 bytes) makes a brute-force guessing to the device ID impossible. However, because the device ID is hard-coded and cannot be changed once it is programmed, this gives rise to another opportunity to make up a phantom device. In particular, an attacker buys a TP-LINK device and activates it by logging it in the cloud. By analyzing the APK of mobile app mentioned in Section III-B1, attacker can easily extract the device ID and the mac/hwid tuple from the JSON messages during device-app communication to bypass device legitimacy checking (F1). As a result, if the device is reused by another user, the attacker can make up a phantom device with the same device ID.

We now discuss circumstances in which a victim may use a device which was once possessed by an attacker. First, the consumer ownership of an IoT device can be changed once it is programmed. Because of the legitimacy checking, an effective phantom device can make up a unique 2-tuple information consisted of a MAC address and a hardware id hwid. Device legitimacy checking is actually implemented by checking the matching between the device ID and the mac/hwid tuple. As before, on the top of Figure 7, we show the regular workflow of a legitimate TP-LINK device. Appendix A shows a complete sequence diagram. The device is first provisioned with the WiFi credential (Step A.1), and then with the user account information Alice (Step A.2). Next, the device registers itself by providing the device ID A, mac/hwid tuple, as well as user account information Alice to the cloud (Step A.3). The cloud binds the device ID A with Alice after verifying the matching between device ID A and the mac/hwid tuple.

![Sequence Diagram for Normal Device Life-cycle and Remote Device Substitution Attack](image)

Then, Alice can remotely or locally control/monitor the device with her mobile app.

On the bottom of the figure, the attacker Trudy who once owned the device, launches the remote device substitution attack. With the device ID and the mac/hwid tuple, she leverages the flaw F3 to log in a phantom device (Step T.1). At this time, the device ID A is still bound with Alice. Since the phantom device has the same device ID with the real device, the cloud is fooled to believe that the device is reused with another IP address. Therefore, the cloud disconnects the original connection with the real device and establishes a new connection with the phantom device. However, when the real device does not receive the heartbeat message for a while, it automatically logs in the cloud again and puts the phantom device offline. Now, the real device and the phantom device are in fact competing for connection with the cloud. To win the competition, the attacker configures the phantom device to frequently login (Step T.2). As a result, the legitimate user Alice still appears to “control” a device through her mobile app, although this device is actually a phantom device rather than the real device. In this sense, the attacker secretly substitutes Alice’s device with a phantom device under control.

D. Attack Impact

**Privacy concerns.** In normal operations, when the victim uses the mobile app to send a remote control command to the cloud, the cloud forwards the command to the “device”. Unfortunately, in the remote substitution attack, the real device has been replaced by a phantom device controlled by the attacker. As a result, all the control commands from the victim are exposed to the phantom device and further to the attacker, leading to privacy/habits leakage.

**Falsified data.** Unlike the hijacking attack, the attacker can also leverage the phantom device to manipulate the returned data (e.g., sensor data, current firmware version) to the victim,
thus deceiving or misleading the victim. Imagine that even attackers hijack a smart-thermometer, they can only monitor the temperature of victim’s home but cannot manipulate it because smart-thermometer does not have interface to set temperature. However, if attackers substitute the smart-thermometer, they can manipulate arbitrary readings to legitimate users. If the thermometer is linked to other mission-critical devices, these devices could be misled. For example, by altering the thermometer status, the cloud could be misled to send a falsified command that operates the air conditioner in an unexpected way. In some cases, more severe consequences can happen.

In theory, our attack model is applicable to all the device models across solutions, except that the prerequisites differ slightly from each other. In our experiments, we have verified the effectiveness of our attack on not only TP-LINK devices (smart WiFi plug with model HS100, smart WiFi LED bulb with Model LB110) but also Alink devices (RIWYTH mobile remote HD monitor with model RW-821S-ALY 2.3.3, TCL cleaning robot with model S533), Joylink devices (BULL smart WiFi plug 2 with model GN-Y2011, BroadLink smart WiFi plug with model SP mini3) and XiaoMi devices (smart WiFi plug with model HS100, smart WiFi LED bulb with sensor values that severely deviate from normal, the cloud could make an obviously wrong decision that is perceptible by a security-savvy user.

VI. Other Threats

In this section, we introduce other security threats by leveraging security flaws shown in Table I. Due to limited space, we do not explain the concrete exploit to each solution. Instead, we only discuss general ideas behind these attacks.

A. Firmware Theft

To protect intellectual property (IP), most IoT manufacturers employ certain tamper-resistant techniques to seal their integrated circuits. This also applies to the flash chip, which stores proprietary firmware. With otherwise leaked firmware, the attacker can easily perform reverse-engineering to it, causing IP theft and harming the company. Although, attackers can dump firmware physically, it requires real devices and involves sophisticated techniques such as removing the coating and welding debugging interface. Because most IoT devices support Over-The-Air (OTA) update, which downloads the firmware from the cloud, the attacker can obtain the different device firmware at large-scale by making up a phantom device that issues an update request (directly or indirectly), which can greatly save attacker cost, time, and effort. Specifically, attacker configures phantom devices as any device model at first. Then, he makes phantom device log in the cloud and send firmware update request to cloud. Although the device-cloud commutation is encrypted, the firmware download URL replied by cloud is carried on a sequence of plaintext HTTP packets. Finally, attacker can download the firmware from the URL.

In the experiments, we were able to use phantom devices to emulate almost all kinds of device models in different solutions, including 1,355 device models of Alink products, 543 device models of Joylink products, 118 device models of XiaoMi products, and 18 device models of TP-LINK products. However, many manufacturers do not actually upload their firmware to the cloud. Eventually, we were able to collect more than 200 different kinds of firmware, including 63 from Alink solution, 37 from Joylink solution, 89 from MIJIA solution, and 16 from KASA solution.

B. Illegal Device Occupation

At a time, only one legitimate user is allowed to bind a smart home device. Therefore, the IoT cloud allows a device ID to be associated with one user account. If the attacker can predict the device IDs of unsold devices and use phantom devices to bind them with some accounts, these devices cannot be registered anymore after sale. We call this attack illegal device occupation. In essential, this attack makes new devices unavailable to legitimate consumers, causing a form of denial-of-service attack.

Of all the four smart home solutions, this attack only applies to Alink solution. As indicated by the device ID generation rule in Section IV-A, for Alink solution, by mutating over a set of legitimate device identity information, the attacker can churn out hundreds of thousands of phantom devices that occupy the device IDs of the corresponding unsold devices, which significantly affects their devices sales. JD solution is immune to this attack because their device IDs also depend on the user account information, which is unpredictable. In XiaoMi and TP-LINK solutions, long enough device ID is hard-coded in the device. It is obvious that the attacker cannot obtain the device ID beforehand.

C. Local Device Hijacking

Local device hijacking aims to control a smart home device locally. In particular, if the attacker joins in the same LAN with the victim device, he could send arbitrary control commands or pull the real-time status of the device (F5 in Figure 4F5). As explained in Section III-C, the root reason of local device hijacking is the blind trust to local messages. In particular, there is no authentication required for app-to-device communication. In our experiments, we found that all the tested solutions except for Alink are subject to local device hijacking attack.

It is interesting to note that this attack can not only be used to hijack the victim device locally, but also be used in a combination with other flaws to cause other security breaches. For example, in the JD solution, the device ID does not only rely on device identity information, but also involves user account information, which is transmitted to the cloud through
the mobile app. Thus, a local attacker can re-register the victim device (due to F3), then he replaces the returned device ID sent by mobile app with a device ID which is bound with his own account, and sends it to the victim device. Finally, the victim device directly accepts attacker’s device ID (F5) and rewrites its original device ID. As a result, after device re-logs in the cloud, attacker can even remotely hijack the device.

VII. DISCUSSION

In this section, we first discuss broader impact of this work from two aspects – how to extend the general idea of the proposed attacks to other types of smart devices, and how commercial companies take advantage of the phantom device for malignant competition. Then, we suggest some defensive approaches to mitigate the proposed attacks.

A. Impacts

1) Going Beyond WiFi Devices: In this paper, we focus on WiFi-based smart home devices. However, our attacks are also applicable to smart home devices with other wireless communication modules from two dimensions.

First, the attacker can leverage already exploited WiFi devices to control others. For example, a Xiaomi smart gateway has both a WiFi module and a ZigBee module. After hijacking the gateway through the WiFi interface, the attacker can further harvest all the connected ZigBee devices as well.

Second, following the general idea of the phantom device, the attacker can forge ZigBee or Bluetooth devices because the legitimacy checking is the same for both WiFi devices and others. Using a phantom device, the attacker can launch a subset of the proposed attacks listed in Table II e.g., firmware theft and illegal device occupation. However, as these devices are behind the gateway (in the case of ZigBee) or smartphone (in the case of Bluetooth), it is impossible to remotely hijack or substitute such devices.

2) Malignant Competition: The proposed attacks also have some implications for commercial competition. For example, malicious competitors could steal IP from other companies, and rig the market share by controlling the number of “active” devices.

IP Theft. As mentioned in Section VI-A, the competing company can steal the rival’s firmware and reverse engineer it to steal proprietary IP. This kind of behavior harms fair competition and hinders technique advance.

Statistic Manipulation. By churning our hundreds of thousands of phantom devices, the malicious company could rig the number of active devices in the market. This has two implications. First, by increasing the market share of its own, the company can present an eye-catching year-end report. Second, by increasing the number of activated devices of its rival, its rival could be overcharged by the solution provider. This is because some solution providers bill cooperative manufacturers based on the number of activated devices connected to its cloud. The unscrupulous manufacturer can use phantom devices to register a large number of non-existing devices under the name of its rival, causing financial loss to it.

User Experience Disruption. In the illegal device occupation attack, unscrupulous manufacturers can potentially take over a large number of their rival’s in-stock products. When these products are sold, the consumers will have a terrible user experience including out-of-service.

B. Mitigation

In this section, we propose some defensive design suggestions to better protect smart home devices in the first place.

Strict Device Authentication. In the registration phase of all the tested solutions, the cloud performs certain identity checking to ensure that it talks to a genuine device. However, we have clearly shown that existing authentication are not adequate. This is also the root reason why a phantom device could talk to the cloud. We suggest that the cloud deploys different authentication mechanisms depending on the computation capability of the device. For example, for high-end devices powered by Intel or ARM Cortex-A processors, the manufacturer should embed a unique client certificate into the device. For resource-restricted devices powered by microcontroller, the manufacturer should embed a read-only random number into the device. On the cloud side, the cloud should always check whether the random number matches other less sensitive device information.

Unpredictable Device ID. Because device ID is used by IoT cloud to identified the device, predictable device ID is a necessary condition for a phantom device to launch targeted attacks. Therefore, we suggest smart home solution providers to retrofit the device ID provisioning mechanism so that the attacker cannot easily obtain a valid device ID. Hard coding the device ID is obviously a bad practice and should be avoided.

On the other hand, if the device ID is generated by the cloud during registration, the generation algorithm should mix some hard-to-guess information, such as user account/password, random number, etc.

State Machine Enforcement. According to our findings, all tested solutions do not strictly enforce the validity of the state transitions. For instance, IoT cloud can accept some device requests which should not be allowed in its current state (F3). In addition, if the user does not strictly follow the instructions to operate the device, states of three entities could be out of sync and IoT cloud could move to an unexpected state (F2). In order to prevent the attacker from exploiting unexpected transitions, the three entities should define and maintain their own state machine, and IoT cloud should keep three entities states in sync.

Comprehensive Authorization Checking. Compared with mobile-side commands, IoT cloud does not enforce strict authorization checking to device-side commands and mistakenly trusts any connected devices. For example, in the remote device hijacking attack, a key step is that the phantom device sends an unauthorized unbind command to the cloud.
Device Security. Device security research emphasizes the security and privacy issues in the smart home communication protocols such as BLE, ZigBee, and ZWave [9, 2], [36]. Agosta et al. [2] approached the security and privacy problems involved the key derivation algorithm adopted by the widespread Z-Wave home automation protocol. Ronen et al. [36] described a worm attack which has the potential of massive spread by exploiting an implementation bug in the ZigBee Light Link protocol. Liu et al. [32] first did an security analysis to the Joylink solution, but they focus on communication protocols implementation flaws. For instance, they found that the ECDH key negotiation process during device initial step is vulnerable to MITM attacks. In comparison, the identified flaws in this work are caused by the complexity introduced by the interactions model of smart home solution (e.g., unexpected state transitions). We are the first to reveal unexpected state transitions by constructing three entities state machines. Moreover, many of the proposed attacks are constructed by combining multiple individual flaws.

Access Control. Fernandes et al. [14] revealed that over 55% of SmartApps in the Samsung’s store are over-privileged because the capabilities implemented in the programming frameworks are too coarse-grained. On the other hand, many smart home platforms support trigger-action services such as IFTTT. Fernandes et al. [15] also found that the OAuth tokens for the IFTTT services are over-privileged, which can be misused by attacker to invoke API calls that are outside the capabilities of the trigger-action service itself. Our work focuses on the interaction model of participating entities in the smart home solution, instead of a specific smart home services.

Other Security Problems with Smart Home. With the development of smart home technology, users can control their devices in more convenient ways. However, usability comes at the cost of a large attack surface [43], [14]. For example, inaudible voice, a new attack vector, has been proposed to control Amazon Echo silently [43].

IX. Conclusions

Smart home is playing a more and more important role in our digital life. To seize market share, smart home solution providers shorten the time-to-market by reusing existing architecture and incorporating open-source projects without rigorous review. We disclosed five vulnerabilities by analyzing the complex interactions among devices, IoT cloud, and mobile app. To exploit these vulnerabilities, we leverage a phantom device, which is a software device emulator, to interfere with the interactions of a real product. As a result, the participating entities are misled to diverge from the valid state machines. We show that such unexpected state transitions lead to serious threats to smart home users, including privacy breach and unauthorized remote control. The disclosed architectural vulnerabilities are applicable to multiple major smart
home solutions, and cannot be amended via simple security patches. Therefore, we advocate that smart home solution pioneers endeavor to prioritize the security and privacy of their customers and go through a strict review process before releasing their products.

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APPENDIX
Fig. 8: Sequence Diagram of the Alink Smart Home Solution

Fig. 9: Sequence Diagram of the KASA Smart Home Solution

Fig. 10: Sequence Diagram of the MJIA Smart Home Solution

Fig. 11: Sequence Diagram of the Joylink Smart Home Solution