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Leakage of Authorization-Data in IoT Device Sharing: New Attacks and Countermeasure

Bin Yuan, *Member, IEEE,* Maogen Yang, Zhen Xu, Qunjinming Chen, Zhanxiang Song, Zhen Li, Deqing Zou, and Hai Jin, *Fellow, IEEE*

Abstract—Device sharing among users is a common functionality in today's IoT clouds. Supporting device sharing are the delegation methods proposed by different IoT clouds, which we find are heterogeneous and ad-hoc — IoT clouds use various data (e.g., device ID, product ID, and access token) as authorization certificates. In this paper, we report the first systematic study on how the authorization-data are managed in IoT device sharing. Our study brought to light the security risks in today's IoT authorization-data management, identifying 6 authorization-data leakage flaws. To mitigate such flaws, we propose an approach to hide the authorization-data from the delegatee (a.k.a., the user authorized to access the devices) without disrupting the device sharing services. We propose *SecHARE*, an automated tool to patch the vulnerable IoT clouds. We applied *SecHARE* to 3 popular open-source IoT clouds. Results have shown the compatibility, effectiveness, and efficiency of *SecHARE*. We have made *SecHARE* publicly available.

Index Terms—Cyber-Physical Systems, IoT Security, Authorization-Data Protection

◆

1 INTRODUCTION

Today's IoT (Internet of Things) cloud platforms are providing more and more functionalities to meet the users' various requirements. Device sharing among multiple users is one of the most popular functionalities supported by the mainstream IoT clouds (e.g., AWS IoT [1], Samsung SmartThings [2], Philips Hue [3] and MiHome [4]). Device sharing allows the owner/admin-user to delegate the access right to the device to other users and clouds (which we call the delegatee). Prominent examples include that the owner of a Philips Hue device inviting other Philips users to control her device (by issuing a whitelistID for the delegatee user [5]) and the owner of a SmartThings smart home authorizing Google Home cloud to control her device (by sending the device ID of the SmartThings device and an OAuth token [6] to Google Home cloud). Serving this purpose are the delegation mechanisms proposed by different IoT vendors, which we found are heterogeneous and ad-hoc. In specific, different IoT clouds use different types of data (e.g., device ID, product ID, OAuth token) as the authorization certificates (which we call the `authorization-data`, see Section 3). Also, different types of data are with different changeability, for example, the device ID (set when the device is created) is usually unchangeable, while access tokens are usually changeable (e.g., updated by the owner). Previous researches have revealed that vulnerabilities in these IoT delegation mechanisms could expose users to security and safety risks [5]. However, little have done to systematically study how the authorization-data are managed (e.g., creation, distribution, and deletion) in the real-world IoT clouds.

Risks in poor authorization-data management. Permission issues have always been one of the key concerns of IoT security, and access control community has also been studying delegation of authority issues, finding privacy leaks, incomplete credential revocation, overprivileged authorization, and incorrect policy enforcement [5], [7]–[9]. However, in today's IoT cloud ecosystem, access control is not only distributed but also heterogeneous and ad-hoc, so authorization-data protection remains an open problem. Fernandes et al. [9] found that the vulnerable event management in SmartThings enables the attackers to obtain device identifiers to send fake fire alarms. Bin et al. [5] found that the insecure cross-cloud IoT delegation could also result in the leakage of device information and OAuth token, leading to unauthorized access to the victim devices. Given the severe consequences of authorization-data leakage (e.g., privacy leakage and safety threats), it is emerging to understand and mitigate this problem.

To secure the authorization in IoT, Fernandes et al. [10] presented DTAP to prevent an untrusted trigger-action platform from misusing compromised OAuth tokens, while Andersen et al. [11] presented WAVE, an authorization framework supporting decentralized trust and transitive fine-grained delegation/revocation. However, these approaches require significant changes to the existing IoT cloud platforms and devices. Real-world adoption and deployment of DTAP [10] or WAVE [11] may take a long time, until all compatibility and usability issues are resolved. A timely solution that is lightweight, compatible with existing IoT

- *Bin Yuan, Maogen Yang, Zhen Xu, Qunjinming Chen, Zhanxiang Song, Zhen Li and Deqing Zou are with the School of Cyber Science and Engineering, Hubei Key Laboratory of Distributed System Security, Hubei Engineering Research Center on Big Data Security, National Engineering Research Center for Big Data Technology and System, Services Computing Technology and System Lab, Huazhong University of Science and Technology, Wuhan, 430074, China. Bin Yuan is also with the Songshan Laboratory, Zhengzhou, 452470, China.*
- *Hai Jin is with the School of Computer Science and Technology, National Engineering Research Center for Big Data Technology and System, Services Computing Technology and System Lab, Cluster and Grid Computing Lab, Huazhong University of Science and Technology, Wuhan, 430074, China.*
- *Deqing Zou is the corresponding author. E-mail: deqingzou@hust.edu.cn.*

clouds, and effective at securing the authorization-data is needed.

Findings and impacts. In this paper, we report the first systematical study on how the authorization-data are managed in today's IoT device sharing. Specifically, we studied 6 popular IoT clouds to investigate the life-cycle of the device data, especially the authorization-related device data, which we call authorization-data for short.

Our study shows that, in the absence of security standards/guidance, today's IoT clouds usually develop their homegrown mechanisms to support device sharing, resulting in heterogeneous and ad-hoc authorization-data management. In specific, we find IoT clouds use various types of data with different changeability as authorization-data (see Section 3). Moreover, our study shows that, due to the lack of understanding on the security implications of the authorization-data, today's IoT clouds often adopt vulnerable authorization-data management mechanisms.

We have identified 6 authorization-data leakage flaws in the evaluated IoT clouds (see Section 4). Leveraging these flaws, attackers can use the leaked authorization-data to emulate the victim devices for device state and event forgery attacks (e.g., a fake alarm event), privacy theft attacks (e.g., inferring the absence/presence of the victim via obtaining the state of the victim's devices) and deny of service (DoS) attacks (e.g., disconnecting a sub-device). As shown in Table 1, we summarize the severe consequences of these attacks as falsified data (FD), privacy breach (PB) and deny of service (DoS). Moreover, we found the flaws identified could expose a large number of IoT users and other IoT clouds, as well as organizations, and vendors in various fields, to security risks (Section 6.1). We report all flaws to the relevant parties and have received 5 CNVDs [12] by the time we write this paper.

Defense with shadow authorization-data. To mitigate such flaws, we propose a method that can hide the actual authorization-data from the delegatee to avoid leakage without interrupting the device sharing services. Specifically, when delegating access right to the delegatee, we generate a new copy of authorization-data (e.g., device ID′) that is different from the actual authorization-data (e.g., device ID), and record the mapping relationship between them (e.g., device ID → device ID′). We call the new copy of authorization-data the **`shadow authorization-data`**. Then, we send the shadow authorization-data (device ID′) to the delegatee. Upon receiving the delegatee's request to access the delegated device, we transfer the shadow authorization-data back to the actual authorization-data according to the recorded mapping relationship (device ID′ → device ID) , and then perform authorization check based on the actual authorization-data (device ID). To revoke the delegatee's access right, we delete the shadow authorization-data and the mapping relationship between the shadow and actual authorization-data. Such a workflow can avoid leaking the actual authorization-data to the delegatee users. Moreover, the malicious delegatee users will not be able use the shadow authorization-data to gain unauthorized access to the victim devices after his access right is revoked. In addition, the whole process is made transparent to the users — the delegator and delegatee users can use the device sharing services as usual as they already do in today's IoT systems.

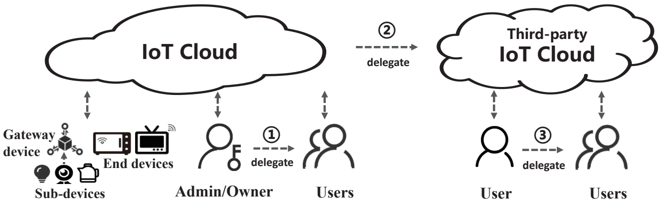

Fig. 1: IoT cloud architecture and its device sharing

Automated patching. Further, we design and implement *SecHARE*, a tool that automatically patches the vulnerable IoT clouds. Specifically, *SecHARE* takes as input a `configuration` file that specifies the names of the sensitive methods operating the authorization-data (e.g., the `assignDeviceToCustomer()` function in ThingsBoard [13] used to share a device to a delegatee user), automatically identifies such methods and inserts necessary operations into the bytecodes for security enhancement (see Section 5). Moreover, *SecHARE* implements an automatic configuration file generator to reduce the manual efforts needed to specify the configuration files (see Section 5.4).

We applied *SecHARE* to 3 popular open-source IoT clouds, ThingsBoard [13], Kaa [14] and JetLinks [15]. Our evaluation shows that *SecHARE* can effectively mitigate the authorization-data leakage flaws with negligible/acceptable overheads and can be easily deployed into today's IoT ecosystem. We have made *SecHARE* publicly available [16].

Contributions. We summarize our contributions as follows:

- *New understanding*. We performed the first systematic study on how the authorization-data are managed in the IoT clouds, which reveals the security-critical weaknesses in today's IoT authorization-data management.
- *New findings*. We investigated 6 popular IoT clouds and identified 6 authorization-data leakage flaws, which expose many IoT devices/users to realistic security risks with severe consequences.
- *New techniques*. We proposed a new method to mitigate the flaws in IoT authorization-data management, and developed/released support for automated securing IoT authorization-data. We implemented our proposed method and demonstrated its usability, efficiency, and compatibility with existing IoT cloud systems. The insights and techniques of our study can help secure not only today's but also future IoT authorization-data management.

2 BACKGROUND

2.1 IoT Cloud Architecture and Its Device Sharing

Device control and its automation. A typical IoT architecture include the IoT devices, the cloud and the user console (e.g., mobile app or web app). To control an IoT device, as shown in Figure 1, the device owner first register her device to the cloud, with the device bound to her user account. To access the device, the owner initiates a request through her user console. Upon receiving the request, the cloud performs an authorization check on the user and

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send the command to the target device if the check passes. Moreover, users can define automation rules (a.k.a., trigger-action rules) for automated device control — when receiving the trigger of the rule, the cloud automatically performs the action. For example, a user can set an automation rule to work in that if the motion sensor detects movement, turn on the light.

Device types. As shown in Figure 1, there are three types of IoT devices: (1) The end device, devices that connect to the IoT cloud directly and do not manage sub-devices; (2) The gateway device, a gateway device connects to the IoT cloud directly and manages/connects to other sub-devices; (3) The sub-devices, a sub-device is managed by and connected to a gateway device. Note that, the sub-devices usually connect to the gateway device through protocols like Zigbee [17], Z-wave [18] and BLE [19], while the gateway device acts as an agent for the sub-devices to communicate with the IoT cloud. A sub-device usually can be added to and removed from the gateway device under the user's operation.

IoT messaging protocol. Many IoT messaging protocols (e.g., MQTT [20], HTTP [21], CoAP [22], LwM2M [23] and AMQP [24]) are used by today's IoT clouds, among which MQTT is the most widely used [25]. MQTT adopts a publish–subscribe messaging pattern [26]. For two clients to communicate with each other, the MQTT server (called the MQTT broker) uses `topic`s to define the message classes; the message receiver (called the subscriber) subscribes to the topics to show its interest in these message classes; the message sender (called the publisher) publishes messages to specific topic(s); upon receiving the published message, the broker identifies the corresponding topic and transmits the message to all its subscribers. To secure the messaging process, before accepting/delivering messages from/to the clients, the MQTT broker usually performs authentication and authorization check based on the `Username`, `Password` or `topic` contained in the messages. Note that, different implementations of MQTT broker might customize such security checks — performing the checks based on other information (e.g., customized `token`s) or even performing no check at all.

Device sharing in IoT clouds. Device sharing among multiple users is commonly supported by today's IoT clouds, which enables the admin-user/owner of the devices to delegate access right to the devices to others.

- *Device sharing within a single IoT cloud*. The owner can share her devices with other users under the same cloud (① and ③ in Figure 1). For example, IoT clouds including HomeKit [27], MiHome [4] and SmartThings [2] enables the owner to invite other users to join the owner's smart home system and delegate access rights to the devices to the invited users.
- *Cross-cloud device sharing*. Cross-cloud delegation [5] is also commonly seen in today's IoT clouds for owners to share the devices with users from third-party clouds (② in Figure 1). Cross-cloud device sharing is usually implemented with OAuth protocol — the delegator cloud issues an OAuth token to the delegatee cloud. In real world, the delegator clouds are usually the clouds maintained by the device manufacturers, such as Philips Hue [3], SmartThings [2] and MiHome [4], while the delegatee clouds are the third-party cloud services providers like Google Home [28] and IFTTT [29].

2.2 Aspect-Oriented Programming

Aspect-oriented programming (AOP) was proposed by Gregor et al. [30], which aims to address the cross-cutting problem during effective application modularization. It can add additional behaviors non-invasively without changing the original design/code. "Weaving" is one of the terms in AOP, which is the process of applying the functionality that needs to be extended to the target object. "Weaving" can be divided into four different types based on the time when the behavior is woven into the target class: (1) Compile-Time Weaving, which weaves the behavior at the source code compilation with a special compiler; (2) Post-Compile/Binary Weaving which weaves the behaviors into the compiled file with a special compiler; (3) Load-Time Weaving which uses a special class-loader to weave the behavior when the class is loaded into the Java virtual machine; (4) Run-Time Weaving which weaves the behavior during the execution of the program. The two most popular frameworks of AOP are AspectJ [31] and Spring AOP [32]. AspectJ supports the former three weaving types, while Spring AOP supports the latter two types. In this paper, we leveraged AspectJ to insert security-enhancement behaviors into the vulnerable IoT clouds with Load-Time Weaving (see Section 5.3).

3 LIFE-CYCLE OF AUTHORIZATION-DATA

To investigate how the authorization-data is managed in today's IoT device sharing, we studied over 10 mainstream IoT clouds, including AWS IoT [1], Alibaba Cloud IoT [33], Google Home [28], Tuya [34], SmartThings [2], IFTTT [29], ThingsBoard [35], Kaa [14], [36], JetLinks [37], ThingsKit [38] and ThingsPanel [39].

Definition of authorization-data. To enable the delegatee user to access the delegated devices, the IoT cloud usually would send certain data to the delegatee user. Such data would then be used for authorization check when the delegatee user attempts to access the devices. We call the data transmitted to the delegatee during device sharing and used for authorization checks during the delegatee's access to the device the authorization-data.

Type of authorization-data. Recall that, in the absence of the standard/guidance on how to securely share devices, the implementation of device sharing by different IoT clouds are heterogeneous. Specifically, various types of authorization-data are used in today's IoT clouds, including public available information (e.g., app-version-name), identifiers (e.g., device ID and product ID), access tokens, MQTT topics, MQTT passwords and HTTP/CoAP URLs.

Changeability of authorization-data. Further, some types of authorization-data (e.g., device ID and product ID) are determined by the IoT clouds and are unchangeable by the users, while other types of authorization-data are changeable under the operations from the authorized users (including both the device owner and the delegatee users). For example, the "endpoint token" of a device under the Kaa Enterprise cloud [36] can be changed by users via revoking the old token and activating a new one.

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Life-cycle of authorization-data. Moreover, we find that the authorization-data could be created, accessed, updated, transmitted, deleted or deactivated in different phases of the device management. We summarize the life-cycle of authorization-data as follows.

- *Add device*. The life-cycle of authorization-data starts with adding the device. Usually, when the owner registers/binds a new device, the IoT cloud determines/generates the unchangable information for the device, which are used as unchangable authorization-data by some IoT cloud. For example, the device ID and application version is used as unchangable authorization-data by SmartThings [2] and Kaa Enterprise [36] respectively.
- *Share device*. When the owner shares a device to the delegatee user, the IoT clouds may generate new authorization-data (e.g., issuing a new access token) or reuse the existing data (e.g., device ID) as authorization-data. Then, the IoT clouds would transmit the authorization-data to the delegatee.
- *Unshare device*. After the owner revokes the access right from the delegatee user, the authorization-data would be removed from the delegatee user's system (e.g., her mobile app). Moreover, the IoT clouds could deactivate/update some of the changeable authorization-data, such as the OAuth token.
- *Query device information*. An authorized user could query the cloud for the device information. The responses to such queries might contain authorization-data. For example, the ThingsBoard [35] transmits the authorization-data of access token to the querying user.
- *Update device data*. The authorized users are usually allowed to update the device data, including both the basic device data (e.g., device name) and the changeable authorization-data (e.g., access token).
- *Access device*. When a user attempts to access a device, the user usually sends to the cloud an access request that carries authorization-data, which is accessed and verified by the cloud for authorization check.
- *Delete device*. When a device is deleted from the IoT cloud, all its information including the authorization-data related to the device would deleted or deactivated by the cloud.
- *Delete user*. Once a user is deleted from the cloud, the data of all devices under the user would be deleted or invalidated.

4 SECURITY OF IOT AUTHORIZATION-DATA MANAGEMENT

In this section, we report a security analysis on the management of authorization-data in IoT device sharing of 6 leading IoT clouds, including ThingsBoard [35], Kaa Enterprise [36], Kaa open-source [14], JetLinks [37], ThingsKit [38] and ThingsPanel [39].

4.1 Problem Scope and Threat Model

As discussed in Section 2.1, the owner can share her devices to other users under the same cloud of the owner or under third-party clouds. In this paper, we mainly focus on identifying and fixing the flaws in the former scenario. We further discuss how our work can help secure the cross-cloud device sharing in Section 7.

TABLE 1: Flaws discovered in popular IoT platforms

	Flaw 1			Flaw 2			Flaw 3			Flaw 4			Flaw 5			Flaw 6		
	FD[1]	PB[2]	DoS[3]	FD	PB	DoS	FD	PB	DoS	FD	PB	DoS	FD	PB	DoS	FD	PB	DoS
Kaa_E*	✓	✓								✓	✓							
Kaa_O*																✓	✓	
$ThingsBoard$				✓	✓	✓				✓	✓							
$ThingsKit$				✓	✓													
$JetLinks$							✓	✓	✓				✓	✓				
$ThingsPanel$													✓	✓				

* Kaa_E is the enterprise version of Kaa. Kaa_O is the open-source version of Kaa.
[1] Falsified Data. [2] Privacy Breaches. [3] Denial of Service attacks.

To this end, we defined two user roles in the IoT system, the administrator and the ordinary user. The administrator (e.g., Airbnb host) is the owner or system admin-user who can delegate other ordinary users (e.g., babysitters, Airbnb guests and tenants) to access her IoT devices. The access of ordinary user is subject to revocation and expiry. We consider the administrator and the IoT clouds to be trusted, while the ordinary user may be malicious and may try to get unauthorized access to IoT devices — which is a well accepted scenario [5], [11], [25], [40], [41]. We assume that the malicious ordinary user will try his best to obtain useful information from the system, such as extracting information from official developer documentations, system logs, network traffic captured by his mobile app. Moreover, we assume that the user is unable to tamper or decrypt data that was not originally intended for their authorized access.

4.2 Authorization-Data Leakage Flaws

Our goal is to systematically study the life-cycle of the authorization-data (e.g., generation, transmission, invalidation, etc.) and to identify authorization-data leakage flaws. To this end, we run the cloud-ends of the aforementioned 6 cloud platforms in our testing servers. We used the MQTTX [42] to simulate the devices supporting MQTT protocol and used Postman [43] to simulate the devices supporting HTTP. We then operated the simulated devices to communicate with the clouds and conducted different configurations/operations in the user consoles of the cloud platforms, simulating the real-world usage of controlling/managing devices. During such simulations, we used Wireshark [44] to collect the traffic between the devices and the cloud platforms. Then, we mainly checked whether the data transmitted to the delegatee users is critical to authorization and whether we can use such data to gain unauthorized access even after revocation. At last, we identified 6 flaws in these IoT clouds. We elaborate on each of them as follows.

Flaw 1: MQTT topic leakage. Kaa Enterprise [36] is an IoT cloud platform that supports device sharing among users and supports multiple messaging protocols including MQTT, CoAP and HTTP. When a device connects to the Kaa Enterprise cloud using MQTT protocol, the MQTT topic is used as authorization-data. That is, Kaa Enterprise authorizes the device based on the topic contained in the messages (see Section 2.1) — only the devices that could provide valid topics are allowed to publish messages to the Kaa

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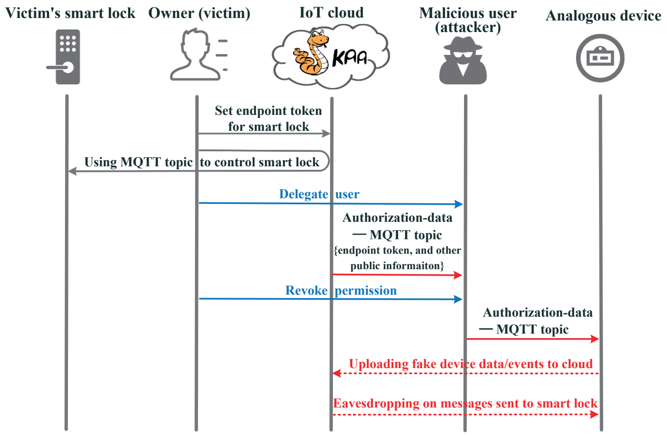

Fig. 2: Flaw 1 — MQTT topic leakage in Kaa Enterprise

Enterprise cloud. To construct a valid topic, Kaa Enterprise requires the owner to set the "endpoint token" (a string) for the device when adding the device. The endpoint token is regarded as a secrecy that can only be accessed/updated by authorized users (including the owner and the delegatee user). With the endpoint token, Kaa Enterprise constructs the topic for the device by adding other publicly available information (e.g., the application version) to the endpoint token. Hence, a typical MQTT topic in Kaa Enterprise could be $kp1/\{application\_version\}/dcx/\{endpoint\_token\}/json$.

However, we found the the authorization-data of Kaa Enterprise cloud (e.g., the MQTT topic) can be obtained by the delegatee user. Recall that, the delegatee user is allowed to update the endpoint token of the delegated device. Therefore, the delegatee user can gain a valid endpoint token by updating it. Using the updated valid token and other public information, the delegatee user can obtain a valid copy of MQTT topic. Note that, updates to endpoint tokens are automatically handled and synced by the cloud and do NOT notify the device owner or affect the owner's use of the device. Moreover, the delegatee user's updates to the endpoint tokens remain valid even after his access right is revoked, resulting in that, the MQTT topic leaked to the delegatee remain valid and unchanged after the revocation. Therefore, a malicious delegatee user could leverage the leaked MQTT topic to send/receive unauthorized messages to/from the Kaa Enterprise cloud after his access right is revoked.

PoC exploit on Flaw 1. To exploit Flaw 1, we used our test account and a MQTT-enabled smart lock (a virtual device) to implement an end-to-end PoC attack. Specifically, as shown in Figure 2, the owner first set the endpoint token of the smart lock on the Kaa Enterprise cloud platform for the victim smart lock to communicate with the cloud. Then, the owner shared the smart lock with the attacker. The attacker then updated the smart lock's endpoint token and obtained a valid MQTT topic. After that, we let the owner revoked the attacker's access right. Then, we wrote a program using Python (publicly available at [16]) to pretend to be the victim smart lock to communicate with the Kaa Enterprise cloud. As shown in Table 1, we were able to send forged messages (FD) and receive unauthorized messages (PB) to/from the cloud.

Flaw 2: MQTT username leakage. In addition to the MQTT topic leakage (see Flaw 1), we found that the MQTT username is also used as authorization-data and could be leaked to the attackers in ThingsBoard [35] and ThingsKit [38].

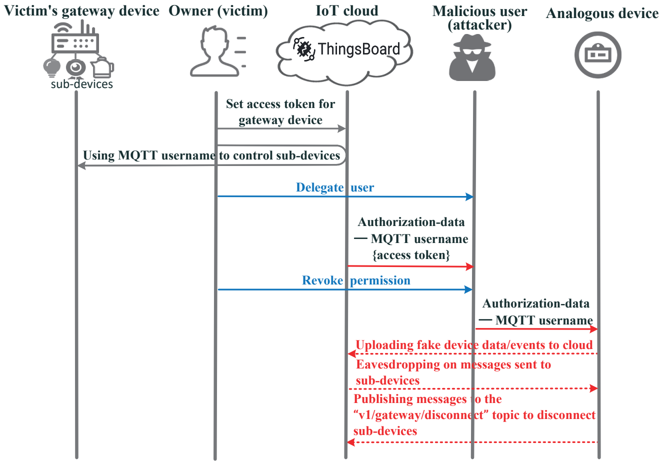

Fig. 3: Flaw 2 — MQTT username leakage in ThingsBoard

ThingsBoard is a popular open-source IoT platforms that supports MQTT, HTTP, CoAP and LwM2M. When a MQTT-enabled device communicates with the ThingsBoard cloud, the device is required to provide a valid MQTT username, which is used for MQTT's authentication/authorization check (see Section 2.1). Therefore, a valid and unique MQTT username will be assigned to the device when the owner adds the device to ThingsBoard. Specifically, during the device adding, the owner or the cloud would set an "access token" for the new device. The access token then is used as the MQTT username for the device to communicate with the ThingsBoard cloud.

The problem we identified here is that the access token is accessible to the delegatee user — when the delegatee user queries the ThingsBoard cloud for the information about a device delegated to him, ThingsBoard would send information that contains the device's access token to the delegatee user. Moreover, the access token does NOT change or become invalid after the owner revokes the access right from the delegatee user. Consequently, a delegatee user with malicious intentions could obtain the MQTT username (a.k.a., the access token) when he is authorized and reuse the leaked MQTT username to stealthily communicate with the cloud after he loses access right to the device.

PoC exploit on Flaw 2. We conducted a PoC attack to exploit the Flaw 2 in ThingsBoard. In specific, we configured a virtual gateway device connected to other sub-devices in the ThingBoard cloud (Figure 3). We then temporarily shared the gateway device to the attacker. At this point, the attacker can obtain the access token from the ThingsBoard cloud to form the authorization-data (e.g., MQTT username). After we revoked the attacker's permission, we tried to use our attacking programs ([16]) to communicate with the ThingsBoard cloud. We found that, with the leaked MQTT username, we were able to send forged messages and receive messages to/from the ThingsBoard cloud. In addition, we were able to publish messages to the *v1/gateway/disconnect*

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topic to disconnect the sub-devices under the victim gateway from the cloud (DoS in Table 1).

Note that, We found the exact same problem discussed above in the ThingsKit [38] platform. An attacker can leverage Flaw 2 to send falsified data and receive private information of the victim to/from the ThingsKit cloud (see Table 1).

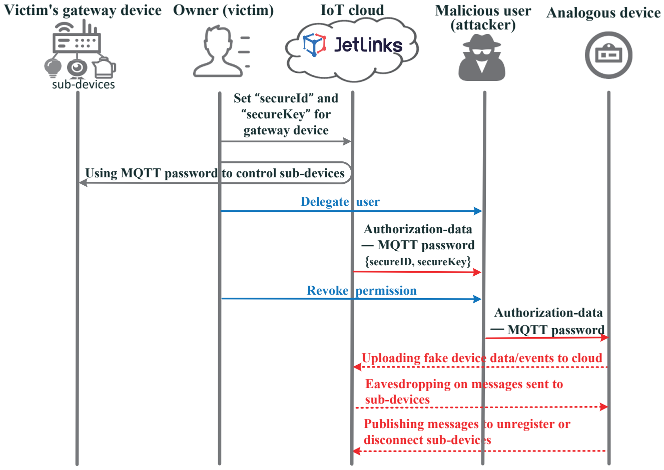

Fig. 4: Flaw 3 — MQTT password leakage in JetLinks

Flaw 3: MQTT password leakage. JetLinks [37] is another open-source IoT cloud platform that supports MQTT protocol and uses the MQTT password as authorization-data [45] for devices to communicate with the cloud. Specifically, when adding a new device, the owner needs to set a "secureKey" and a "secureId" for the device. To communicate with the cloud, the device sends MQTT packages with the MQTT password set to *md5(secureID+"|"+timestamp+"|"+secureKey)* and another field filled with the timestamp in plaintext. Upon receiving such a package from the device, JetLinks checks the correctness and freshness of the MQTT password using the timestamp received and its own copy of secureId and secureKey. Only the devices that pass such checks are allowed to communicate with the cloud.

The problem in JetLinks cloud is similar to that in ThingsBoard (Flaw 2). The authorization-data (e.g., the secureId and secureKey) is obtainable to the delegatee user and does NOT change after the owner revokes the delegatee user's access rights. Therefore, a malicious delegatee user can use the leaked authorization-data to communicate with the cloud even after his access right is revoked.

PoC exploit on Flaw 3. Exploiting Flaw 3 is also similar to the exploitation of Flaw 2, as shown in Figure 4. The key challenge was for the attacker to obtain the secureId and secureKey. This was done by capturing the traffic between the attacker's user console (the web-based application provide by JetLinks) and the JetLinks cloud. In our PoC attack, the attacker successfully extracted the secureId and secureKey from the packets/traffic sent from the JetLinks cloud to the user console. Then, with our PoC attacking programs [16], the attacker was able to conduct all the three attacks (e.g., FD, PB, and DoS in Table 1).

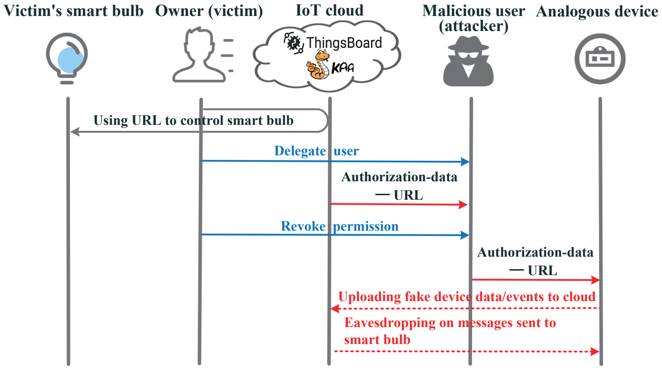

Fig. 5: Flaw 4 — URL leakage in ThingsBoard and Kaa Enterprise

Flaw 4: URL leakage. Recall that, ThingsBoard supports HTTP for the devices to communicate with the cloud. We identified the problem of URL leakage in the HTTP messaging of the ThingsBoard. Specifically, in ThingsBoard's HTTP messaging, the URL (e.g., *http(s)://host:port/api/v1/access_token/telemetry*) is used as the device's authorization-data and is unique for each device. Anyone who knows the URL can communicate with the cloud on behalf of (or pretend to be) the device. The problem here is that the URL could also be leaked to the attacker, who then could use the URL to communicate with the ThingsBoard cloud maliciously.

To make matters worse, even an attacker who has never been authorized to access the device before can obtain the URL and conduct the attacks (see Table 1). For example,the attacker could monitor all the traffic in the victim's home WiFi network to extract the URL.

PoC exploit on Flaw 4. The PoC exploitation of Flaw 4 is rather straightforward. As outlined in Figure 5, we let the victim owner shared the virtual smart bulb to the attacker. The attacker was able to extract the URL from the traffic between his user console and the ThingsBoard cloud. After the owner revokes the attacker's access right, we found the attacker was able to communicate with the ThingsBoard cloud using our PoC attack programs [16].

Note that, we found the same problem (Flaw 4) in the Kaa Enterprise platform (see Figure 5), which also supports HTTP messaging. We omit the detailed discussion for simplicity.

Flaw 5: Device identifier leakage. We found that the device identifier is used as authorization-data in JetLinks's HTTP messaging and ThingsPanel's MQTT messaging, both of which are vulnerable.

In JetLinks's HTTP messaging, JetLinks exposes a public URL (http://server-address/report-property) for the devices to communicate with the cloud (Figure 6). To authenticate and authorize a device, JetLinks requires the device to provide a valid device ID (which is created when the device is added to the cloud and is unchangeable) in the packets sent to the URL. However, such an unchangeable authorization-data (e.g., device ID) is accessible to the delegatee users (by querying the device data from the cloud), which leads to the FD and PB attacks in JetLinks as shown in Table 1.

Moreover, in ThingsPanel's MQTT messaging,

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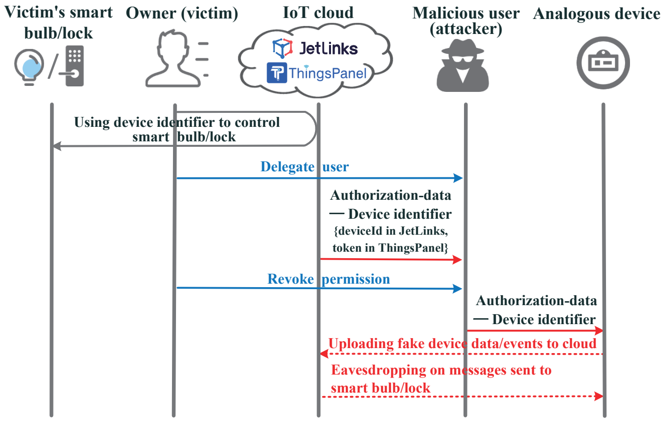


Fig. 6: Flaw 5 — Device identifier leakage in JetLinks and ThingsPanel

ThingsPanel uses the same MQTT topic for all the devices and requires each device to provide its unique identifier (e.g., the token set by the owner when adding the device) for authorization check. However, as shown in Figure 6, when a device is shared to the delegatee user, the delegatee user can obtain the device's token in message push log of the device. Such data leakage could lead to the FD and PB attacks in ThingsPanel as shown in Table 1.

PoC exploit on Flaw 5. We confirmed Flaw 5 in both JetLinks and ThingsPanel with our PoC attacking programs [16].

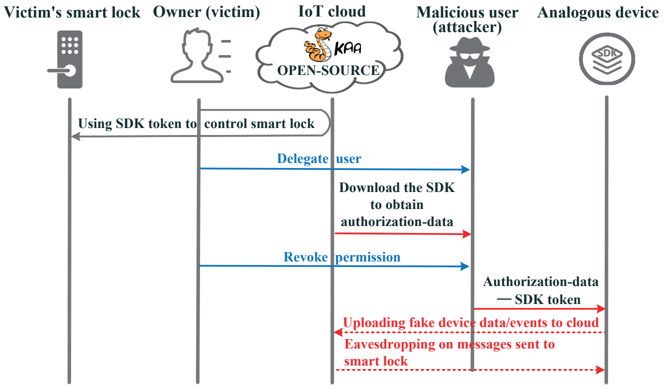


Fig. 7: Flaw 6 — SDK token leakage in Kaa open-source

Flaw 6: SDK token leakage. Kaa open-source [14] is a open-source IoT cloud platform that supports flexible device definition and creation. Specifically, Kaa open-source provides the owners an endpoint SDK (a library that exposes many useful APIs for the device to use) for them to create devices with various functionalities. Each time a device is created, the cloud would generate a unique token (which we call the SDK token) for the device and store the SDK token into the device's own copy of SDK. The SDK token is then used for the cloud to perform authorization check when a device attempts to communicate with the cloud (Figure 7). Moreover, when the owner authorizes a delegatee user to access a device, the delegatee user is allowed to download the SDK of the delegated device. As a result, the delegatee user can further obtain the device's SDK token from the downloaded SDK. Besides, the SDK token does NOT change when the owner revokes the delegatee user's access right. Therefore, a malicious delegatee user can leverage this flaw to stealthily communicate with the cloud, resulting in FD and PB attacks (see Table 1).

TABLE 2: Received CNVD IDs

IoT cloud platform	CNVD ID
`ThingsBoard` (Flaw 2, Flaw 4)	*CNVD-2022-27848*
`JetLinks` (Flaw 3, Flaw 5)	*CNVD-2022-38276*
`Kaa Enterprise` (Flaw 1)	*CNVD-2022-41097*
`ThingsKit` (Flaw 2)	*CNVD-2022-56053*
`ThingsPanel` (Flaw 5)	*CNVD-2022-84690*
`Kaa open-source` (Flaw 6)	*CNVD-2023-38442*

PoC exploit on Flaw 6. In our PoC attack, as outlined in Figure 7, the owner used the Kaa open-source SDK to create a virtual smart lock (whose SDK token is set as *2wXVH-wXD6TR_cAdr5RoWal6K0Q* by the cloud). Then, the owner delegated the smart lock to the attacker. The attacker downloaded the smart lock's SDK and wrote an attacking program [16] that used the SDK along with the SDK token in it to connect to the cloud. We found that the attacking program can still successfully communicate with the Kaa open-source cloud after the attacker's permission was revoked.

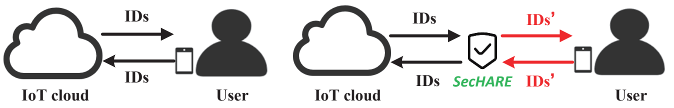
Responsible disclosure. We report all flaws to relevant parties, who all acknowledged the seriousness of the problems. We have received 6 CNVDs [12] (see Table 2).

Ethical consideration. The PoC attacks are conducted using our own accounts/devices in our testing environment, without disrupting the real-world IoT services or users.

5 SYSTEM DESIGN AND IMPLEMENTATION

In this section, we elaborate on the design and implementation of *SecHARE*, an automated tool to patch the vulnerable IoT clouds for authorization-data protection, which can be easily applied to today's IoT clouds. We have made *SecHARE* publicly available [16].

5.1 Overview



(a) Without our proposed defense

(b) With our proposed defense

Fig. 8: The authorization-data transmission between the cloud and the users (with and without our proposed defense)

At a high level, the IoT clouds should ensure that the authorization-data transmitted in device sharing will not be leaked to attackers, preventing the unauthorized access to the devices from the attackers. To fix the authorization-data leakage flaws (discussed in Section 4), we propose a usability preserving protection method that replaces the actual authorization-data with the shadow authorization-data and transmits the shadow authorization-data to the delegatee user without interrupting the device sharing services — the owner and the delegatee users can use the IoT services as normal as they already do in today's IoT systems. The security enhancement is achieved by hiding the actual authorization-data from the delegatee users. In specific, as illustrated in Figure 8a, without our protection, the actual authorization-data (e.g., IDs) is transmitted to the delegatee user during device sharing, which could lead to the problems discussed in Section 4. In contrast, *SecHARE* works as a *proxy* during authorization-data transmission: 1) when the cloud sends authorization-data (e.g, ID) to the delegatee user, *SecHARE* generates a shadow copy of the authorization-data (e.g., ID') and send it to the user; 2) when a message from the user arrives at the cloud, *SecHARE* converts the shadow authorization-data to the actual authorization-data and the inner process logic of the cloud uses the actual authorization-data for further processing. Notably, the shadow authorization-data is generated using the same format of that of the actual authorization-data (e.g., a 20-bit string). As a result, impacts on the normal functionalities introduced by *SecHARE* can be minimized. To this end, we developed *SecHARE* to automatically patch the vulnerable codes of the IoT clouds.

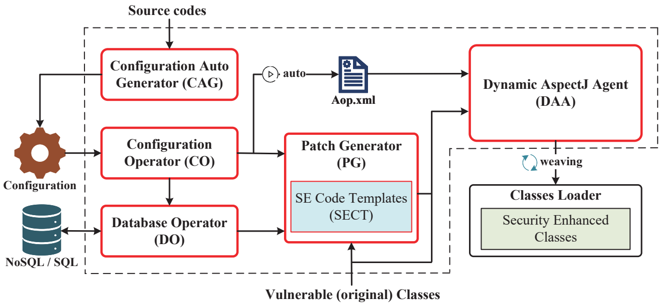


Fig. 9: The architecture of *SecHARE*

Architecture. Since different IoT clouds use different types of authorization-data and define different methods/functions to create, access, update, transmit, delete and deactivate the authorization-data. We need a method to automatically identify the methods/functions that operate the authorization-data and patch these methods/functions to fix possible authorization-data leakage in a way that does not impact the usage of IoT services.

To this end, as shown in Figure 9, we built *SecHARE*, which is composed of 5 components: a Configuration Operator (**CO**), a Database Operator (**DO**), a Patch Generator (**PG**), a Dynamic AspectJ Agent (**DAA**), and a Configuration Automatic Generator (**CAG**). Essentially, *SecHARE* generates patches for the vulnerable cloud with the predefined Security Enhancement Code Templates (`SECT`) based on our usability preserving defense (see Section 5.2) and leverages the AspectJ [31] (an AOP framework, see Section 2.2) framework to insert these patches into the IoT cloud when the classes are loaded into the Java virtual machine.

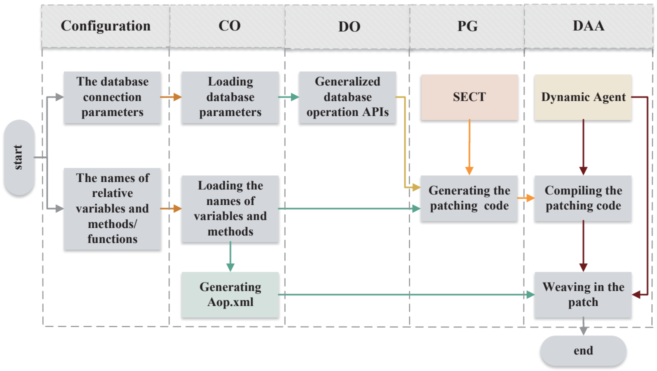


Fig. 10: The workflow of *SecHARE*

Specifically, to apply *SecHARE* to patch an IoT cloud, we need to deploy and execute *SecHARE* along with the IoT cloud. Then, as shown in Figure 10, `CO` takes as input the `configuration` file (which specifies the methods/functions operating the authorization-data) to generate the `Aop.xml` file for the `DAA` to use[1]. `CO` also outputs information (e.g., the specified authorization-data to protect and the names of methods need to be patched) to the `PG`. Along with the database operation APIs provided by `DO`, the `PG` then generates the patch codes. Taking as input the `Aop.xml` and the patch codes generated by `PG`, the `DAA` leverage the AspectJ framework to compile the patching codes and weave the additional/security-enhancement behaviors (defined by the patch codes) into the IoT cloud's original vulnerable classes at loading time, allowing the IoT cloud to use Security Enhanced Classes to manage/operate the authorization-data.

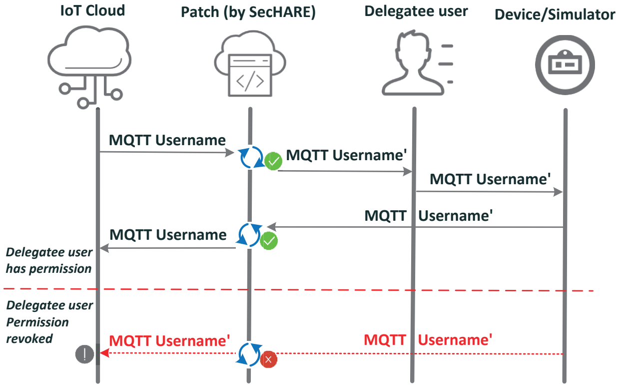


Fig. 11: Usability preserving defense to Flaw 2

5.2 Usability Preserving Defense

IoT device sharing is vital to today's IoT cloud. Almost all IoT clouds support such functionality, for users widely require it (e.g., sharing devices to family members, Airbnb guests, babysitter, etc.). Therefore, the key to authorization-data leakage solution is how to avoid disrupting the normal IoT device sharing service. Our solution is to provide a

[1] The `Aop.xml` and the `configuration` file contains the same information. The `Aop.xml` is organized in the format supported by AspectJ, while the `configuration` file is with better readability.

usability preserving defense that is made transparent to the users — they can use the device sharing services as normal as they already do.

Specifically, our proposed defense leverages a simple yet effective data mapping scheme to prevent authorization-data leakage. In specific, after the owner shares her device to a delegatee user, the IoT cloud needs to transmit the authorization-data to the delegatee user. Instead of transmitting the authorization-data directly to the delegatee user (as today's IoT clouds do), we generate a shadow copy of authorization-data, record the mapping relationship between the actual authorization-data and the shadow authorization-data and then transmit the shadow authorization-data to the delegatee user. The delegatee user then uses the shadow authorization-data to access the delegated device. Upon receiving the access request from the delegatee user, the cloud extracts the shadow authorization-data from the request, transfers the shadow authorization-data to the actual authorization-data based on the mapping records stored by the cloud, and uses the actual authorization-data for authorization check. When the owner revokes the delegatee user's access right, the cloud delete the shadow authorization-data and its corresponding mapping record. Hence, even if the shadow authorization-data is leaked to and preserved by the malicious delegatee users, he will not be able to leverage the shadow authorization-data to gain unauthorized access to the device. Note that, all the operations (e.g., data-mapping, data-storage and data-deletion) are performed automatically by the backend cloud, which are transparent to the users. Therefore, we could fix the authorization-data leakage problems in today's IoT clouds while preserving their usability.

Example. Taking Flaw 2 (Section 4) as an example, Figure 11 illustrates how our defense operates the authorization-data and shadow authorization-data. Recall that, ThingsBoard uses the `MQTT Username` as authorization-data in its MQTT messaging. Therefore, to share the device to the delegatee user, ThingsBoard generate the shadow authorization-data (`MQTT Username`′) for the actual authorization-data (`MQTT Username`). Then, the `MQTT Username`′ is transmitted to the delegatee user, instead of `MQTT Username`. When the delegatee user is authorized, he can use `MQTT Username`′ to access the device normally. After the delegatee user's permission is revoked, ThingsBoard removes the `MQTT Username`′. As a result, the delegatee user can no longer access the device, even if he preserved the `MQTT Username`′ when he was authorized.

Discussion. Recall that, today's IoT clouds use both changeable and unchangeable authorization-data. When the changeable authorization-data is leaked to the attacker, the owner might help to mitigate the problem by changing/updating the authorization-data each time he revokes access right from a delegatee user. However, this approach relying on users to ensure the security may not be ideal. First, real world owners might not be aware of the problem or forget to update the authorization-data. Second, the device might be shared to multiple delegatee users. Updating the authorization-data when revoking one of the delegatee users might cause the other delegatee users cannot access the device, either. If the unchangeable authorization-data is leaked to the attacker, the owner has little to do to ease the problem since she cannot update the authorization-data.

5.3 Automated Patching

How to adapt to different IoT clouds' implementations of device sharing and keep the performance overhead to minimal are vital to automated patching.

Adaptability and scalability. The implementations of device sharing in today's IoT clouds are heterogeneous — defining multiple methods/functions to operate the various types of authorization-data. Hence, it is particularly important for the patch scheme to adapt to most (if not all) of the IoT clouds and even scale to new IoT clouds. For better adaptability and scalability, we consider the follow aspects.

- `Configuration` *guided patching*. Based on our understanding on the lifecycle of authorization-data (see Section 3), we cannot generate a single unified patch for all of the clouds. Instead, we leverage a `configuration` that specifies the methods/functions operating authorization-data defined in a specific IoT cloud to generate the unique patch for the cloud. Note that, our patch scheme is general and scalable. To patch another IoT cloud, we simply ask for a new `configuration` file and patch the cloud accordingly. We further developed `CAG` to reduce the manual efforts for specifying the `configuration` file (see Section 5.4).
- *Minimal changes to the system*. It is also essential to ensure easy deployment and minimal changes to existing systems. To this end, we adopt the AOP (see Section 2.2) technique to only weave security-enhancement behaviors into the original system without breaking the overall workflow/logic design. Moreover, the weaving is done automatically by our tool at the loading time of the classes, requiring minimal (or no) manual intervention from the IoT cloud manager/developer.
- *Supporting SQL/NoSQL database*. Our scheme stores the mapping relationships between the authorization-data and shadow authorization-data in the database. Also, such data are stored in concordance with the data managed within the cloud platform, and are inaccessible to users. Consider the usage of different types of databases, we develop `DO` to provide universal APIs for database access and implement `DO` to support both SQL and NoSQL databases.

Minimal performance overhead. Low end-to-end latency is important in IoT device control. To minimize the latency overhead, we only introduce additional computation to the cloud-side while the client-side (the device and user console) remains unchanged. Since the clouds are usually with strong computing capabilities, the overhead should be negligible (see Section 6.2).

5.4 Automatic Generation of Configuration Files

Essentially, the `configuration` file specifies the implementation details of device sharing, including which data/variables are used as authorization-data and which methods/functions operate the authorization-data. We expect the users of *SecHARE* (e.g., a developer/manager of the IoT cloud) to provide the `configuration` file, for they would already know the implementation details. Nevertheless, we develop `CAG` to help the users to specify the

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TABLE 3: Common words/affixes at some phases of the life-cycle of authorization-data

Phase[1]	**Common Words**[2]
`Add Device`	*add, save, create, regist-*
`Delete Device/User`	*del-, remove, cancel*
`Share Device`	*auth-, right, permission, assign, claim, grant, deploy, delegate*
`Unshare Device`	*auth-, right, permission, revoke, unassign, disclaim, undeploy*

[1] Some phases of the life-cycle of authorization-data.
[2] The key words/affixes within the phase.

`configuration` file, reducing the manual efforts needed to use our tool.

`CAG` mainly focuses on automatically identify the names of methods/functions that operate the authorization-data. Note that, it is possible for `CAG` to identify a non-related method/function as method/function that operates the authorization-data. Hence, we let `CAG` list all the methods/functions it identified and let the user to delete or add methods/functions from/to the list.

Specifically, we investigated 50 IoT cloud projects on Github to learn the naming pattern/habit of the IoT programming. We found that the methods/functions defined in the 8 different phases of the authorization-data's lifecycle (see Section 3) can be divided into two categories: (1) The methods/functions that have a common naming pattern, including *Add device*, *Delete device*, *Delete user*, *Share device* and *Unshare device*; (2) The methods/functions that do not have a common naming pattern, including *Query device information*, *Update device data*, and *Access device*.

For the methods/functions in the former category, `CAG` can quickly identify them based on the common key words/affixes used in them (as listed in Table 3) via simple string matching. For the methods/functions in the latter category, we conduct static source code analyses to obtain the information of each method/function to determine whether its parameters or return values contains authorization-data. Notably, Natural language processing (NLP) can help to identify the method/function names, which is discussed in Section 7. Moreover, we build an AST model for the source code to obtain the calling relationship of the methods/functions. With the calling relationship, we could remove (some of) the caller methods/functions from the `configuration` file, since we only need to insert/weave the callee method/function for authorization-data protection.

5.5 Implementation of *SecHARE*

We present the implementation of *SecHARE* as follows with its source codes released online [16].

The `configuration` and `CAG`. As aforementioned, the `configuration` (provided by the user of *SecHARE*) specifies the names of the variables/methods/functions related to the authorization-data. To help automatically generate the `configuration` file, `CAG` uses the QDox [46] to extract the definitions of the classes/interfaces/methods from the source code and uses Spoon [47] to build the AST model. Note that, the `configuration` also specifies the information needed to connect/access the database (e.g., the name of the database, the username and the password needed to connect the database), which is used to store the relationship between the authorization-data and shadow authorization-data.

The `CO`. Taking the `configuration` file as input, `CO` generates the `Aop.xml` file in the format required by AspectJ [48]. The `Aop.xml` file would then be input to the `DAA`. Also, from the `configuration` file, `CO` extracts the names of relative variables and methods/functions and sends them to the `PG`. At last, `CO` sends the database-related parameters (e.g., database username, password, etc.) to `DO`.

The `DO`. `DO` provides generalized database operation APIs, supporting both SQL and NoSQL databases. Currently, `DO` supports most SQL databases (a.k.a., Relational Database Management Systems) and the popular NoSQL database MongoDB [49].

The `PG`. Based on our defense (see Section 5.2), we create the `SECT` to include all the possible behaviors needed to insert/weave into the vulnerable IoT clouds. Specifically, we define code templates for data transferring, database read, database write and database deletion. Then, `PG` locates the vulnerable methods/functions in the original classes based on the input from `CO`, and automatically generates the patching codes using the templates in the `SECT` and the APIs provided by `DO`. Example-1 illustrates how `PG` patches the *shareDeivce()* method. Specifically, *shareDeivce()* calls the *getDevice()* to obtain the authorization-data (e.g., device ID) and transmit the authorization-data to the delegatee user with the *sendToDelegateeUser()* method. `PG` patches such a progress in that: (1) adding line 10 to randomly generate the shadow authorization-data to ensure data uniqueness (in specific, we used the *RandomStringUtils.randomAlphanumeric()* API [50] to generate the data); (2) adding line 11 to store the mapping relationship of the authorization-data, shadow authorization-data and user's identity; (3) replacing line 13 with line 12 to return the shadow authorization-data (instead of authorization-data). Note that, we maintain the data mapping at the user-level. Since a single user typically possesses a limited number of devices, collisions between device mappings are expected to be infrequent.

The `DAA`. The `DAA` is an AspectJ agent [51] that can be loaded into the running Java virtual machine. It takes inputs as the `Aop.xml` and the patching codes from `PG` to weave the patches into the original vulnerable classes when the Class Loader of the Java virtual machine loads the class files, forming the Security Enhanced Classes.

6 EVALUATION

In this section, we discuss the impacts of authorization-data leakage flaws and evaluate the performance of *SecHARE*.

6.1 The Impacts of Authorization-Data Leakage

Prevalence of vulnerable authorization-data management. Bin et al. [5] identified several authorization-data leakage flaws in cross-cloud delegation, while we focused on the

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Example 1: Patching shareDevice()

```
shareDevice (device, delegateeUser) {
    ...
    deviceID = getDevice(device, delegateeUser);
    sendToDelegateeUser(deviceID, delegateeUser);
    ...
}

getDevice(device, delegateeUser) {

    ...
    shadowData = generateShadowData(device.ID);
    storeMapping(device.ID, shadowData,
delegateeUser.ID);
    return shadowData;
    ~~return device.ID;~~

}
```

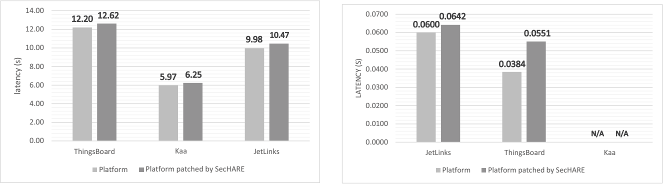
security issues of authorization-data management within a single IoT cloud. As shown in Table 1, we identified 6 new flaws with 3 of them (Flaw 2, Flaw 4 and Flaw 5) affecting more than one IoT cloud, which shows the prevalence of the authorization-data leakage problem.

Scope of the impact. The 4 open-source IoT clouds we analyzed (i.e., ThingsBoard [13], JetLinks [15], Kaa open-source [14] and ThingsPanel [52]) are among the most popular IoT projects in the open-source community, with over 17K stars on GitHub in total. The other 2 commercial IoT cloud platforms (i.e., Kaa Enterprise [36] and ThingsKit [38]) serve many enterprises (including Lenovo, Alibaba cloud and NET4.IO [36], [38]) and customers, and connect millions of devices in various field (e.g., smart energy, smart agriculture, smart home, and industrial Internet of Things [53], [54]). Therefore, security loopholes in these IoT clouds can bring huge damage to the real world IoT applications.

6.2 Performance Evaluation

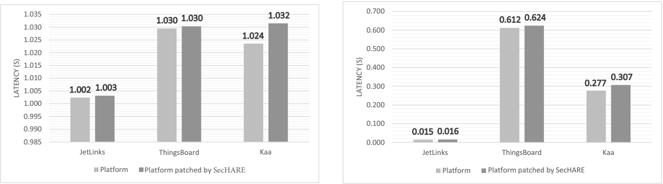
Selecting IoT clouds for flaw identification. Since we focused on the security issues in the IoT device sharing within a single cloud, we only studied the clouds that support such functionality and enforce access control mechanisms. Also, we prioritized the general IoT clouds — the clouds can be applied to multiple IoT scenarios (e.g., smart home, smart city, smart energy, etc.). At last, we prioritized the clouds with better popularity — more GitHub stars for the open-source clouds and more customers for the commercial clouds.

Selecting IoT platforms for defense evaluation. *SecHARE* fixes the flaws by patching the source codes of the clouds. Hence, we only evaluated *SecHARE* upon the open-source clouds. Further, multiple programming languages (e.g., Java, Go, C++, C, etc.) are used to implement the open-source IoT clouds. However, according to the Eclipse Foundation IoT survey [55], Java is the top choice with a popularity of 66.5%. Therefore, we applied *SecHARE* to the three open-source IoT clouds written in Java (e.g, ThingsBoard, JetLinks, and Kaa open-source).



(a) system startup latency

(b) device creation latency



(c) device connection latency

(d) device control operation latency

Fig. 12: Cost assessment of *SecHARE* applied to 3 cloud platforms (Kaa open-source platform cannot accurately measure the latency of creating a device).

Efficiency. To evaluate the efficiency of *SecHARE*, we deployed 3 popular open-source IoT platforms (i.e., ThingsBoard, Kaa open-source, and JetLinks) in our test server (with Intel Core i7-9700 cpu, 16GB memory). With each cloud, we carried out multiple operations (including system startup, device creation, device connection, and device control) before and after it is patched by *SecHARE* (experimental programs and data are publicly available at [16]). We repeated the system startup operation for 20 times and measured the time. As shown in Figure 12a, the overhead on startup time introduced by *SecHARE* is 400 ms averagely. For the device creation, device connection and device control operations, we repeated the experiments for 2000 times. As shown in Figure 12b, Figure 12c and Figure 12d, the average overheads are 10.39 ms, 3.17 ms and 14.25 ms respectively. We believe such overheads is negligible.

Performance overheads. In order to assess the impact of deploying *SecHARE* on a real-world cloud platform, we also conducted a series of performance evaluations on our test server. Specifically, we measured the CPU and run-time memory usage for 1000 device creation and data querying operations on the ThingsBoard both before and after deploying *SecHARE*, respectively. We observed an increase of only 0.14% in CPU usage and 0.16% in memory usage, indicating that the performance overheads introduced by *SecHARE* is negligible.

6.3 Security benefit

As discussed in Section 4, the attacker can leverage the leaked authorization-data to communicate with the cloud even after his access right is revoked. We evaluated whether the attacker can achieve that in the cloud that has been patched by *SecHARE*.

Specifically, we set up 3 different devices: the temperature sensor, the smart window, and the gateway device. Each device was assigned a specific operation, such as uploading device data/events, receiving remote control commands, and managing gateway sub-devices. As depicted in

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TABLE 4: The authorization-data transmitted to the user with and without our protection

Device	Access token (without protection)	Shadow access token (with protection)
`Tempeature`	*7G1o5tuLlioLrkTs6s5d*	*9KCsJanYJ0XaRsMijQyk*
`SmartWindow`	*K0BC07q02zj1E06byFU5*	*11IreMrM1bVaOfHwc8vh*
`Gateway`	*EWXzP88urDF1twim4KIEE*	*xSnIgvaRozojurfD8mgn*

TABLE 5: The logs output by the cloud platform under different operations before and after the patch

Event	Log
upload device data/events	[1]Connecting to the cloud-host with an access token. Client connected! Uploading device data with interval 3 (sec)...
	[2]Connecting to the cloud-host with an access token. Disconnecting...

receive remote control commands	[1]Connecting to the cloud-host with an access token.
	Client connected!
	Receive: {
	timestamp: 1656328161692
	topic: v1/devices/me/rpc/request/1
	body: {”method”: ”setStatus”,
	”params”: ”{\”set_status\”:\”close\”}”
	}
	}

	[2]Connecting to the cloud-host with an access token. Disconnecting...
management gateway sub-devices	[1]Connecting to the cloud-host with an access token. Client connected! Timestamp-1656328417946: gateway_subdevice_1 disconnected! Timestamp-1656328417946: gateway_subdevice_2 disconnected!
	[2]Connecting to the cloud-host with an access token. Disconnecting...

[1] Attack on the ThingsBoard cloud not patched by SecHARE.
[2] Attack on the ThingsBoard cloud patched by SecHARE.

Table 4, we ensured that the authorized user did not have access to the actual authorization-data, which remained undisclosed to them within the SecHARE-patched cloud. Next, we assessed the scenario in which a malicious user (e.g., an attacker), possessing retained authorization-data (access token), attempts to exploit vulnerabilities in an unpatched cloud platform, as illustrated in Table 5. Through our evaluation, we observed that the attacker could engage in data forgery attacks by uploading device data, privacy leakage attacks by receiving remote control commands, and denial-of-service attacks by disconnecting/logging out the gateway device, thereby disrupting the service of subdevices. However, when these operations were attempted within the SecHARE-patched cloud platform, the system effectively denied all unauthorized access attempts, preventing harm caused by the leakage of authorization-data. This indicates that our proposed defense can effectively mitigate the flaws.

7 DISCUSSION AND FUTURE WORK

Manual efforts to secure an IoT cloud. As discussed in Section 5.3, *SecHARE* requires the user to provide a `configuration` file. Specifying the `configuration` file requires manual efforts. Although we developed `CAG` to reduce such manual efforts, certain efforts are still needed when `CAG` is not able to determine the exact methods/functions.

Towards fully automated analyses. To further improve the automation of *SecHARE*, NLP techniques can be used to automatically locate/identify the method/function names in the source code. By parsing functions and extracting features from the source code, NLP can make *SecHARE* more accurate and efficient. Therefore, in future work, we aim to explore the feasibility and effectiveness of integrating NLP techniques into *SecHARE* to improve its automation and accuracy.

Protection of cross-cloud device sharing. Although we only applied *SecHARE* to secure the device sharing within a single IoT cloud, our general defense can also help to secure the cross-cloud device sharing. For example, Bin et al. [5] found that the deviceID of the SmartThings device (which is treated as a credential in SmartThings) could be leaked to a malicious delegatee user in the Google Home. Leveraging the leaked deviceID, the malicious user can control the victim's SmartThings devices that he is not entitled to access. This problem can be also fixed with our data mapping scheme. When the SmartThings transmits the deviceID to the Google Home, the SmartThings could generate a new deviceID (denoted as deviceID′) and send the deviceID′ to Google Home. Upon receiving a request from Google Home carrying deviceID′, the SmartThings can transfer the deviceID′ to deviceID, and perform authorization check based on deviceID. When revoking the access right of Google Home, SmartThings can delete the deviceID′, thus to fix the problem without disrupting the normal IoT service. Note that, SmartThings should NOT delete deviceID, since it is also used by other users/applications in the SmartThings. Also, SmartThings can NOT refuse to send the identifier of the delegated device to the Google Home, since the access delegation protocol of Google Home requires such information.

Supporting more languages. Diverse programming languages, including Java, Go, and C#, are employed in the implementation of contemporary IoT clouds. Presently, *SecHARE* has adopted the AspectJ framework specifically to support Java programming language. Notably, analogous frameworks are available for other programming languages, such as GoAOP or Go-Aspect for Go, and AspectDNG for C#. In future work, we aim to explore the applicability of these frameworks to accommodate diverse programming languages. It is worth noting that the fundamental concept underlying our proposed defense mechanism is general in nature, thus facilitating its extension to other IoT clouds.

8 RELATED WORK

IoT platform security. In the rapid development of the IoT, the IoT cloud plays an important role. Chen et al.

[56] and Zhou et al. [57] have reported flaws found in device management for IoT clouds, demonstrating that leakage of device identity can have serious consequences. However, they only discovered the vulnerabilities without proposing any defense mechanisms. Yuan et al. [5] proposed a semi-automated tool to detect cross-cloud IoT delegation vulnerabilities. In contrast, our work focuses on authorization issues within individual cloud platforms and provides an automated protection tool (*SecHARE*) to mitigate the authorization-data leakage problem. Moreover, most of the existing work is mainly for specific platforms, such as SmartThings [7], [9], [58]–[65], IFTTT [10], [66], [67] and AWS Alexa [68], [69]. By contrast, our work is to provide a tool to protect different cloud platforms. Besides that, some works [7], [62], [66], [70] provide methods to protect sensitive information or data flow in IoT apps, whereas our work is focuses on protecting authorization-data only in the cloud.

IoT permission sharing. Permission issues have always been one of the key concerns of IoT security and have been widely studied [9]–[11], [58], [59], [71]–[74]. Fernandes et al. [9] first reported that the coarse-grained capability design leads to over-privileged and the inability of the event subsystem to adequately protect events carrying sensitive information in SmartThings. Additionally, access control is not only distributed but also heterogeneous and ad-hoc in today's IoT cloud ecosystem.

To cope with the new application scenario, Jia et al. [58] focused on permission protection and proposed ContexIoT, a fine-grained context-based permission system for SmartThings to provide context integrity for IoT programs at runtime. Tian et al. [59] presented a user-centric, semantic-based authorization design called SmartAuth to help users avoid overly privileged applications in SmartThings. These researches primarily focus on the permission management of the applications, without consideration of dynamic user authorization scenarios or proposing methods to secure the authorization-data.

Fernandes et al. [62] proposed a privacy-preserving system called FlowFence, which attempts to address the ineffectiveness of existing permission-based access controls in controlling sensitive data flows in applications by embedding the data flow patterns expected by users. However, this work mainly tries to prevent malicious IoT applications from abusing the sensitive data (e.g., data collected by the IoT sensors). In contrast, *SecHARE* focuses on securing the data used for authorization and preventing unauthorization access in a shared IoT scenario.

Furthermore, Fernandes et al. [10] introduced *Decentralized Action Integrity* to prevent an untrusted trigger-action platform from misusing compromised OAuth tokens. Andersen et al. [11] presented WAVE, an authorization framework offering *decentralized trust*, which supports transitive fine-grained sharing and revocation. However, these efforts, while meeting the current complex IoT authorization needs, require all parties to work together following the same framework APIs and are more difficult to apply and deploy to the real world. In contrast, our work only adds a few changes to the cloud platform to realize automatic protection of authorization-data. Moreover, our tool can adapt to a variety of authorization-data and is compatible with different cloud platforms.

9 CONCLUSION

In this paper, we systematically study how the authorization-data are managed in the real-world IoT device sharing and its security implications. Our research reveals that authorization-data leakage is prevalent in the IoT clouds, with 6 flaws identified in 6 popular IoT clouds. To mitigate the problem, we proposed *SecHARE* to automatically patch the vulnerable codes of the IoT clouds. We applied *SecHARE* to 3 open-source IoT clouds. Our evaluation shows that *SecHARE* is easy to use by the IoT vendors, effective and efficient in securing authorization-data. Our new understanding and new techniques will provide better protection for today's IoT cloud platforms, as well as those to be built in the years to come.

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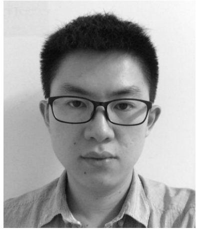
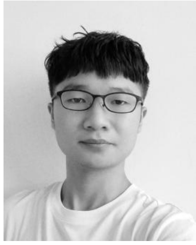


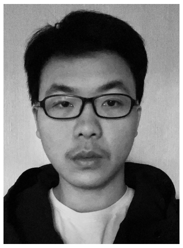
Bin Yuan is an Associate Professor at Huazhong University of Science and Technology (HUST), Wuhan, China. Bin received his B.S. and Ph.D degree in Computer Science and Technology from HUST in 2013 and 2018, respectively. His research interests include software-defined network security, network function virtualization, cloud security, privacy and IoT security. He has published several technical papers in top conferences/journals, such as USENIX Security, CCS, IEEE TSC, IEEE TNSM, IEEE TNSE, IEEE IoT Journal and FGCS.



Maogen Yang is currently a master student at Huazhong University of Science and Technology (HUST), Wuhan, China. Maogen received his B.S. degree in Computer Science and Technology from Anhui Normal University in 2020. His research interests include cloud security, privacy and IoT security.

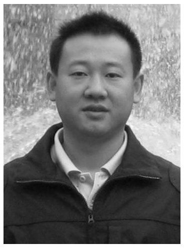
Zhen Xu is cuurently a master student majoring in Cyber Science and Engineering in Huazhong University of Science and Technology(HUST) . Zhen has received his B.S. degree in Cyber Science and Engineeringng from HUST in 2022. He is interested in cloud, operation system and IoT security.

Qunjinming Chen is currently master degree candidate in School of Cyber Science and Engineering at Huazhong University of Science and Technology(HUST), Wuhan, China. He received his B.S degree in Cyber Science and Engineering from Huazhong University of Science and Technology in 2022. What he interests in include network protocol and IoT security.



Zhanxiang Song is currently a master student at Huazhong University of Science and Technology (HUST), Wuhan, China. His research interests include cloud security, software security and IoT security.

Zhen Li is an Associate Professor at Huazhong University of Science and Technology, Wuhan, China. She received the Ph.D. degree in Cyberspace Security at Huazhong University of Science and Technology in 2019. She was a Postdoctoral Fellow at the University of Texas at San Antonio, USA, from 2019 to 2021. She is a member of the IEEE and a member of the ACM. Her research interests mainly include software security and artificial intelligence security.



Deqing Zou is a Professor of Computer Science at HUST. He received his PH.D at HUST in 2004. His main research interests include system security, trusted computing, virtualization and cloud security. He has been the leader of one “863” project of China and three NSFC (National Natural Science Foundation of China) projects, and core member of several important national projects, such as National 973 Basic Research Program of China. He has applied almost 20 patents, published two books (one is entitled “Xen virtualization Technologies” and the other is entitled “Trusted Computing Technologies and Principles”) and more than 50 High-quality papers, including papers published by IEEE Transactions on Dependable and Secure Computing, IEEE Symposium on Reliable Distributed Systems and so on. He has always served as a reviewer for several prestigious Journals, such as IEEE TPDS, IEEE TOC, IEEE TDSC, IEEE TCC, and so on. He is on the editorial boards of four international journals, and has served as PC chair/PC member of more than 40 international conferences.

Hai Jin is a Cheung Kung Scholars Chair Professor of computer science and engineering at HUST. Jin received his PhD in computer engineering from HUST in 1994. In 1996, he was awarded a German Academic Exchange Service fellowship to visit the Technical University of Chemnitz in Germany. Jin worked at The University of Hong Kong between 1998 and 2000, and as a visiting scholar at the University of Southern California between 1999 and 2000. He was awarded Excellent Youth Award from the National Science Foundation of China in 2001. Jin is the chief scientist of ChinaGrid, the largest grid computing project in China, and the chief scientists of National 973 Basic Research Program Project of Virtualization Technology of Computing System, and Cloud Security.

Jin is a Fellow of IEEE and CCF, and a member of the ACM. He has co-authored 22 books and published over 700 research papers. His research interests include computer architecture, virtualization technology, cluster computing and cloud computing, peer-to-peer computing, network storage, and network security.