Multi-User Multi-Device-Aware Access Control System for Smart Home

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Abstract

In a smart home system, multiple users have access to multiple devices, typically through a dedicated app installed on a mobile device. Traditional access control mechanisms consider one unique trusted user that controls the access to the devices. However, multi-user multi-device smart home settings pose fundamentally different challenges to traditional single-user systems. For instance, in a multi-user environment, users have conflicting, complex, and dynamically changing demands on multiple devices, which cannot be handled by traditional access control techniques. To address these challenges, in this paper, we introduce Kratos, a novel multi-user and multi-device-aware access control mechanism that allows smart home users to flexibly specify their access control demands. Kratos has three main components: user interaction module, backend server, and policy manager. Users can specify their desired access control settings using the interaction module which are translated into access control policies in the backend server. The policy manager analyzes these policies and initiates negotiation between users to resolve conflicting demands and generates final policies. We implemented Kratos and evaluated its performance on real smart home deployments featuring multi-user scenarios with a rich set of configurations (309 different policies including 213 demand conflicts and 24 restriction policies). These configurations included five different threats associated with access control mechanisms. Our extensive evaluations show that Kratos is very effective in resolving conflicting access control demands with minimal overhead. We also performed two user studies with 72 smart home users, one to better understand user’s needs in before the design and the other to test the efficacy of Kratos.

1 Introduction

Cyberspace is expanding fast with the introduction of new smart home technologies dedicated to making our homes automated and smarter [3, 38]. This trend will only continue, and billions of smart devices will dominate our everyday lives by the end of this decade [31, 32]. The smart home systems typically allow multiple devices to be connected to increase the overall efficiency of the home, and to automate daily tasks, making it more convenient for its occupants. Devices as simple as a light bulb to ones as complicated as an entire AC system can be connected and exposed to multiple users. The users then interact with the devices through different smart home applications installed through a mobile host app provided by the smart home vendors.

Traditional access control mechanisms proposed for personal devices such as computers and smartphones primarily target single-user scenarios. However, in a smart home system (SHS), multiple users access the same smart device, typically via an app (e.g., SmartThings App) installed on their smartphones or smartwatches (a controller device), which can cause conflicting device settings. For instance, a homeowner may want to lock the smart door lock at midnight while a temporary guest may want to access the lock after midnight. Also, current smart home platforms do not allow the conflicting demands of the users to be expressed explicitly. Finally, the current access control mechanism in smart home platforms offer coarse-grained solutions that might cause safety and security issues [5, 7, 19, 35]. For instance, smart home platforms often give automatic full access to every user added to the SHS [13, 29]. With full access, a new user can easily add new unauthorized users or reconfigure the connected devices [39] and cause safety issues [1, 8, 9]. For instance, a temporary guest can acquire sensitive information of the homeowner or a rogue user can leave the smart lock open for unauthorized physical access. In these real-life scenarios, current smart home platforms cannot fulfill such complex, asymmetric, and conflicting demands of the users as they can only handle primitive and broad controls with static configurations. Once the setup is done, smart home platforms do not allow fine-grained controls or dynamic conditional choices to meet the complex demands of users.

In this paper, we introduce Kratos, a multi-user multi-device-aware access control system designed for the smart homes. We designed Kratos based on an access control user study with 72 smart home users. Kratos introduces a formal policy language that allows users to define different policies for smart home devices, specifying their needs. It also implements a policy negotiation algorithm that automatically solves and optimizes the conflicting policy requests from multiple users by leveraging user roles and priorities.
Lastly, KRATOS governs different policies for different users, reviewing the results of the policy negotiation and enforcing the negotiation results over the smart home devices and apps. We implemented KRATOS in a real multi-user multi-device smart home system (SHS) that include 17 different sensors and actuators. We further evaluated KRATOS performance on 289 different policies including 115 demand conflicts and 38 restriction policies. We also assessed the performance of KRATOS against five different threat models. KRATOS resolves demand conflicts and detects different threats with 100% success rate in a multi-user smart home system with minimal overhead. Finally, we performed a usability study among 43 smart home users. Overall, KRATOS achieved an average rating of 4.6 out of 5 based on user-friendliness, demand, deployment, and effectiveness.

Contributions: The main contributions of this work are as follows:

- Although the user survey is not the major focus of this work, we first conducted an access control study with 72 different smart home users to understand the need for multi-user multi-device access control mechanisms in SHS.

- We introduced KRATOS, a multi-user and multi-device access control mechanism for SHS. KRATOS implements a flexible policy-based user controls to define user roles and understand users’ demands on smart home platform, a formal policy language to express users’ desires, and a policy negotiation mechanism to automatically resolve and optimize conflicting demands and restrictions in a multi-user smart home system.

- We implemented KRATOS on a real SHS using 17 different smart home devices and sensors. Further, we evaluated its performance with 289 different policies provided by real users. Our evaluation results show that KRATOS effectively resolves conflicting demands and detects different threats.

- Finally, we performed a second usability study with 43 different smart home users to understand the effectiveness of KRATOS. Our usability results showed that KRATOS achieves an average of 4.6 ratings out of 5 from the users based on user-friendliness, demand, deployment, and effectiveness.

Organization: The remainder of the paper is organized as follows. In section 2, we present the main findings of our access control study and discuss shortcomings of existing access control mechanisms in SHS. In Section 3, we articulate the problem with a use case and explain our threat model. Later, we detail the architecture of KRATOS in Section 4. Section 5 articulates the implementation of KRATOS in a real-life setting. In Section 6, we evaluate the performance of KRATOS in resolving and optimizing diverse user demands and in detecting different threats in a SHS. In Section 7, we discuss the findings extracted from the usability study of KRATOS. The benefits of KRATOS are presented in Section 8. Finally, Section 9 discusses the related work and Section 10 concludes the paper.

2 Motivation and Definitions

2.1 User Study

We first conducted a user study to understand the real needs for multi-device multi-user access control systems in smart home settings, and later designed an access control system that aligns with those needs. Although the user study is not the primary goal of this work, it is instrumental to understand the users’ needs in a multi-user smart home environment. To conduct our user study, we obtained appropriate approvals from Institutional Review Board (IRB) and provided monetary compensation to each participant. While prior works established the need of access control mechanisms in smart home systems, they do not cover users’ expectations in an effective access control system [16]. In our study, we asked the participants a total of 28 questions organized in three different categories including (1) user characterization, (2) smart home setting preferences, and (3) user preferences in multi-user multi-device scenarios. Additionally, we asked for the users’ expectation regarding design features and implementation of access control system which are missing in the prior works. In Appendix E, we provide example questions included in our user study and detailed results.

User Characterization. We surveyed a total of 72 smart home users. We recruited the smart home users with an open call for participation in our website to avoid any bias in our study. With the questions, we aimed to fully characterize the group of users, their households, and their experiences regarding smart home systems. Our participants were aged between 15-44 years and 88.1% of them owned or were planning to buy smart home devices. Most of the users preferred/used Google Home as a smart home platform followed by Samsung SmartThings, and Apple HomeKit. As per the technical experience of the users, 77.1% participants knew how to set up a smart device and 51.4% participants could install and use different smart home apps. Finally, we characterized the smart home environment the participants used by questions about the household characteristics. All of the participants lived in a multi-user environment and 90% of the total participants shared smart home devices with at least one other user. This indeed provides a positive potential environment to multi-user access control systems.

Smart Home Setting Preferences and Characterization. In this part of the user study, participants answered several questions regarding the need of an access control mechanism in the smart home system. 69.4% of the total participants considered other users’ preferences while installing a smart home device and 80.6% of the participants shared access with other users in a multi-user environment. The majority of users (62 out of 72 participants) also agreed that smart home systems should have an interface that can be regularly checked by the device owner to control the access rights of the devices. We also asked the participants about guest access control in a smart home system where 86.1% of the participants experienced the need of revoking access request for specific devices. In summary, we found that the device owners
frequently had to deal with conflicts as a result of different desires and settings changed by other members of the household. Additionally, the device owners wanted to have controls regarding who accesses the devices and desire limited access for the users that are not fully trusted.

**Multi-user/Multi-device Access Control.** Finally, we assessed the need for the access control mechanisms, and received feedback from the users on the design and implementation of such mechanisms. Most of the participants (80.6% users) considered the access control mechanism as an essential feature of the smart home system and 58.3% users were willing to install additional apps for this feature. We also asked the users for their opinion for priority-based access controls and the majority of the users assigned different priorities based on social relationships (e.g., assigned priority for father, mother, siblings, spouse/partner, guest, etc.). To solve the diverse user demands in a smart home system, participants (71% users) agreed to use an automated policy negotiation system in the access control mechanism. 57.1% of the participants wanted the policy negotiation system to solve the conflicts and notify users about the decisions. For priority-based policy negotiation, 16 users wanted to revoke the lower priority policy while 12 users thought the member with higher priority should negotiate to change the policy. For conflicting policies between the same priority users, participants (72.2%) thought that both the policies should run simultaneously with mutual consent from the users. Additionally, 75% of the participants wanted a monitoring tool to observe the policies from the low-priority users and 74.3% participants wanted the flexibility of removing and updating enforced policies.

**Summary of Findings.** Overall, the users clearly expressed their interest in having an intelligent access control mechanism for a smart home. Also, users suggested that despite a necessary notification system, the access control mechanism should work effectively with minimal user interaction. Finally, users stated that the access control system should be able to differentiate between users with different levels of priority and negotiate access policies dynamically.

### 2.2 Existing Access Control Mechanisms in Smart Homes

Existing smart home platforms offer limited features in access control mechanisms. They often use an edge device (i.e., hub) where smart devices are connected to. Users often control and manage the devices through a mobile phone application provided by the smart home vendor. In some cases (e.g., Samsung SmartThings), the mobile application also enables users to install different smart home apps to control and automate specific tasks on a device. In a multi-user smart home environment, all authorized users can control and change device tasks as the current access control systems in smart home platforms work in a binary control mode where a user gets all the control or no control at all. For example, Samsung SmartThings provides full access to all the connected devices to a user. Moreover, any user gets the privilege to add other users and install new apps in the system. To protect smart devices from unauthorized app installation and device settings, some smart home platforms (e.g., Apple HomeKit) offers two different options, remote access, and editing. In remote access, a new user gets access only privilege to the connected devices. In the editing option, a new user obtains permission for adding or removing any app, device, or user in the system. However, this access control system can not reflect the conflicting demands of the users. We also found that some IoT devices such as August smart lock and RemoteLock offer immature time-based access control mechanisms [21, 27]. These solutions, however, are vendor- and device-specific, thus are not ready and applicable in a multi-device multi-user smart home system. In summary, existing access control mechanism in smart home technologies fail to deliver the diverse and complex user demands in a multi-device multi-user setting.

### 2.3 Terminology

We define several important terms that we use in this work.

**Policy.** We consider Policy as the group of requests made by the users to control device usage in a multi-user smart environment. Based on the nature of request, there are two types of policies.

1. *Demand Policy*. We consider Demand Policy as the group of requests made by a user that define the control rules for a specific device or group of devices in the smart home system. Demand policies can be general (i.e., created by the admin and applied to all the users in the access control system) or specific to a certain user. If a demand policy is general to all users, we define that as *General Policy*.

2. *Restriction Policy*. We consider Restriction Policy as the set of rules that govern the accessibility and level of control of a user or group of users to a certain device or group or devices in the smart home system. In general, restriction policies regulate (1) what devices the user has access to (e.g., the smart thermostat), (2) the time frame in which the user is authorized to use/control the device (e.g., from 2:00 pm to 6:00 pm), and (3) the control setting limits (e.g., minimum temperature and maximum temperature).

**Conflict.** For the purpose of this work, Conflict is defined as the dispute process that is generated from two or more demand policies that interfere or contradict based on the specific requests of the policies. For instance, a conflict occurs when two different users request access control over the same smart thermostat, with different temperatures (e.g., User 1 wants to set the temperature to 72 degrees while User 2 wants to set 78 degrees). Current smart home systems always enforce the latest demand made by the users instantly without considering previous demand made by a different user for the same device.

**Priority.** We call Priority as the importance level of a user that may be used to create preferences for users of higher priority over users with lower priority during new user addition, conflict, and demand negotiation processes. In Section 4, we detail the different priority levels considered in this work.
We assume a smart home setting ($S$) similar to the one depicted in the Figure 1. The smart home has several installed devices to create an automated smart environment. In $S$, four different users – Bob (father), Alice (mother), Kyle (child), and Gary (guest) – interact with the devices. We assume Bob and Alice are the owners of the smart devices and all four users have access to the smart home system through their controller app (installed on their smartphone or tablet). Here, the term access to the smart home system refers to the ability to control the devices, configure the system (add/delete devices), and add new users to the system. We assume that the users are performing the following activities which result in conflicting demands: (1) Bob and Alice are trying to configure the smart thermostat to different temperature values at the same time which results in conflicting demand, (2) Alice tries to restrict Kyle from using the smart coffee machine but smart home system does not allow her, (3) Alice wants to set the smart lock after midnight, but (4) Gary wants to enter the home after midnight which results in conflicting demand, and finally, (5) Gary wants to add his friend Steve in the system who is unknown to Bob and Bob can not restrict the activity. Hence, a new access control system is needed and should be designed to answer the following questions: (1) How Bob and Alice can solve their conflicting demand and use the thermostat simultaneously? (2) How Alice can restrict a specific device for a specific user? (3) How Alice can give exclusive permission to use the smart lock to Gary after midnight? (4) How Bob can limit the access of Gary to add a new user? To address these, we propose Kratos, a fine-grained access control system for the smart home that allows users to resolve the conflicting access control demands automatically, add new users, select specific devices to share, limit the access to specific users, and prevent undesired user access in the system.

### Table 1: Summary of the threat model considered in Kratos

| Threat   | Attack Method     | Attack Example                                                                 |
|----------|-------------------|-------------------------------------------------------------------------------|
| Threat-1 | Over privileged   | A newly added smart home user gets the access to use all the connected devices which can lead to undesired activities in the smart home system. |
| Threat-2 | Privilege abuse   | A newly added smart home user can abuse the granted privilege to perform malicious activities in the smart home system. |
| Threat-3 | Privilege escape  | A newly added smart home user can have an access to the smart home system if the owner forgets to delete the access manually. |
| Threat-4 | Unauthorized access | A temporarily added smart home user can have access to use all the connected devices. |
| Threat-5 | Transitive privilege | A newly added user adds a new user in the system who automatically gets the same privilege level as the owner and may utilize this transitive privilege to perpetrate his/her exploits. |

Kratos considers undesired user access that may arise from existing coarse-grain access control in the smart home. Kratos also considers authorized smart home users trying to change the system settings (e.g., a new temperature range for the smart thermostat) that may result in undesired device actions to other users. Furthermore, Kratos considers threats that arise from inadequate, inaccurate, and careless access control to multi-user multi-device smart home (i.e., transitive privilege). As such, access to a smart home setting granted to unknown parties by an authorized user other than the smart home owner can lead to an unauthorized device usage, which Kratos considers as a malicious activity. Also, if a temporary guest is not timely removed from the system by the authorized user, it may lead to malicious activities such as sensitive information leakage. In Table 1, we detail five different threats that we use later to evaluate the performance of Kratos (§Section 6).

We do not consider any unauthorized user access caused due to malicious apps installed in the system. We also assume that the smart home system is not compromised, which means no malicious user is added automatically at the time of system installation as they are different problems from the contributions of Kratos.
4 Kratos Architecture

In this section, we present the architecture of the Kratos and its main components. Kratos is a comprehensive access control system for multi-user smart home system where users can express their conflicting demands, desires, and restrictions through policies. Kratos allows an authorized user to add new users and enforce different policies to connected smart devices based on the needs of users and the environment. Kratos considers all the enforced policies from authorized users and includes a policy negotiation algorithm to optimize and solve conflicts among users. In designing the Kratos framework, we consider the following design features and goals.

User-friendly Interface. An access control system should have a user-friendly interface to add or remove users as well as assign policies in the smart home system. We integrate Kratos into the mobile app provided by smart home vendors to provide a single user interface to manage users and assign policies in the connected devices.

Diverse User Roles/Complex Relations. In a smart home, users have different roles that an access control system needs to define. For example, a user having a parent role should be able to express controls on a user with a child role, while adults in the same priority class should be able to negotiate the access control rules automatically. To address this design feature, Kratos introduces user priority in the system to define user roles.

Conflict Resolution. As discussed earlier, diverse needs in device usage result in usage conflicts among smart home users in a shared smart home environment. The main challenge of an access control system in a smart home is to resolve these conflicts in a justified way. In addition, users in a multi-user smart home environment should agree with the outcome of conflict resolution provided by the access control system. Kratos uses a novel policy negotiation system to automatically optimize and resolve the conflicting demands among users and institute a generalized usage policy reflecting the needs of all the users. Additionally, Kratos notifies the users the results of the policy negotiation system.

Expressive Control. In a smart home system, a user should be able to express the desired device settings easily. An access control system should provide a simple method to the users to express their diverse needs. Kratos introduces a unified policy language that covers different control parameters (e.g., role, environmental, time, device-specific expressions) in a smart home environment to understand the users’ needs and control the devices accordingly.

Unified Policy Enforcement. All user commands [6] to the devices should go through an access control enforcement layer to provide fine-grained access control in smart home environment. Kratos uses an execution module that checks all enforced policies before executing a user command in the smart home environment.

Figure 2 shows the architecture of the Kratos system. Kratos includes three main modules: (1) user interaction module, (2) back-end module, and (3) policy manager. First, the user interaction module provides a user interface to add new users and assign priorities based on the user’s role. This module also collects user-defined device policies for smart home devices. These device policies and priority assignment data are forwarded to the back-end module via the smart home hub. back-end module captures these data and creates user priority and device policy list for the users. Lastly, the policy manager module gathers user priorities and device policies from the generated lists and triggers policy generation and negotiation process. The following subsections details each module in Kratos and explains how policy generation and negotiation processes are initiated by Kratos.

4.1 User Interaction Module

The user interaction module collects priority assignment data and device policies from the users. It includes two sub-modules: priority assignment and policy input.

Priority Assignment Module. The priority assignment module operates as a user interface to add new users and to assign priorities to the users. Kratos introduces a formal format to specify new users, illustrated as follows: \[ U = [A_{id}, N_{id}, P, D, T], \] where, \( A_{id} \) is the unique ID of the commanding user, \( N_{id} \) is the new user ID that is added in the system, \( P \) is the priority level of the new user, \( D \) is the permission to add or remove devices from the system, and \( T \) is the validity time of the new user in the system. The user priority level is used in the policy generation module to negotiate policies among users and create device policies. For adding a new user and assigning priorities, we consider the following rules to avoid conflicts in the priority assignment.

- Each user has an authority to add new users and assign a priority.
- The Owner of the smart home system will have the highest priority in the system by default.
- Priority in the system is depicted with a numerical value. The lower the priority of a user, the higher is the level of priority. For example, the owner of the hub has the priority of “0”.
- Each user can only assign the same or higher value of the priority to a new user, e.g., a user with a priority of “1” can only assign priority of “1” or higher to a new user.
- If two existing users add the same new user with a different priority level, the user with a higher priority level gets the privilege to add the new user.
- If two existing users with the same priority level assigned different priority levels to a new user, the system notifies the existing users to fix a priority level of the new user.
- Each user can only assign permissions for adding or removing devices to a new user if the commanding user has the same permission.

The priority assignment of Kratos can also be configured to define the roles of the users. For example, the smart home environment in Figure 1, Alice and Bob (parents) can be assigned to priority 0, Gary (guest) can be assigned to priority 2, and Kyle (child) can be assigned to priority 3. We use this...
The clauses have the following structure: \langle users \rangle : \langle devices \rangle : \langle conditions \rangle : \langle actions \rangle. The first part of the policy is \langle users \rangle,
are stored and formatted for policy generation and negotiation. The back-end module has two functionalities: (1) generating user priority list, and (2) generating device policy list.

**User Priority List.** The back-end module collects the credential arrays and creates a database for authorized users and their assigned priorities. Here, all the credential arrays are checked with the priority assignment rules (explained in Section 4.1) and sorted as valid and invalid priority assignments. For each invalid priority assignment, the back-end module notifies the users who initiated the priority assignment. The back-end module also checks the validity of the users added in the user priority list based on the validity time specified in the credential arrays. The back-end module automatically removes user with expired validity and updates the user priority table. A sample user priority list is shown in Figure 5.

**Device Policy List.** The back-end module accumulates all the policies assigned by the users and creates a database based on the device ID. As explained in Section 4.1, the access policy language assigns a device ID to determine the intended policy for each device. This list is updated each time a user generates a new policy for different devices.

### 4.3 Policy Manager Module

The policy manager module collects the user priority list and device policy list from the back-end module and compares different user policies. This module consists of two sub-modules (policy negotiation module and policy generation module) to initiate the policy negotiation and generation processes.

**Policy Negotiation Module.** The policy negotiation module compares all the user-defined policies and detects different types of conflicts based on user priorities and demands. **Kratos** considers three types of conflicts in a multi-user smart home environment: hard conflict, soft conflict, and restriction conflict. A **hard conflict** happens when device policies enforced by two or more users with the same or different priorities have a conflict with each other over different non-overlapping device conditions. For instance, in Figure 1, Alice and Bob try to set the thermostat temperature to two distinct temperature ranges 60-70 and 75-80, respectively. **Kratos** considers this conflicting demand as a hard conflict and starts policy negotiation. On the other hand, **soft conflicts** occur when device policies assigned by the users with the same or different priorities have an overlapping device condition. For example, in Figure 1, if Alice and Bob try to set the thermostat temperature with overlapping ranges (65-75 and 70-80 respectively), **Kratos** considers this as a soft conflict. **Restriction conflicts** occur when a restricted policy disputes with a device policy. As an example, in Figure 1, Kyle (child) wants to access the coffee machine, but Alice restricts the access for Kyle which results in a restriction conflict. In **Kratos**, a policy negotiation algorithm is developed to resolve the policy conflicts and trigger policy generation module to create policies that are acceptable to all authorized users.

**Policy Negotiation Algorithm.** For policy negotiation, **Kratos** considers two essential research questions: (1) How does **Kratos** handle the policy conflicts between users with the same and different priority levels?, and (2) How does **Kratos** handle restriction policies without affecting smart home operations? In the following, we address these questions.

The policy negotiation algorithm processes all the policies and computes the negotiated results by modeling the users’ authorities (classes, roles) in a multi-layer list. Figure 5 illustrates this model. User authorities are split into ordered classes. Class 0 has the highest priority, and a higher class number means a lower priority. Each class may include a list of users (or roles as roles are just a set of users). Users at the same priority class shares the same priority. **Kratos** considers three types of conflicts between user policies after users are classified into authorities (more details in Appendix B).

When two different policies include clauses of the same user’s access for the same device, there can be an interference between those clauses. Any such possible interference is further checked to disclose the potential conflicts. In this, hard conflicts can happen when two interfering clauses dictate different actions for some overlapping cases or dictate the same action for never overlapping cases. In other words, when policies have no possible way of cooperation or compromising, (e.g., Alice demands 60-70 range while Bob demands of 75-80 range for the same thermostat). In such cases, **Kratos** detects a hard conflict; however, if the same action exists with some common overlap while opposite actions never occur together, such interference is a soft conflict. Moreover, conflicts are further categorized as **Priority Conflicts or Competition Conflicts** based on the priority of policy owners. When the conflict happens between users’ policies who have different priority classes, **Kratos** defines a priority conflict. However, if the users have the same priority, competition conflicts happen. Additionally, if any interference is caused by the nature of action requested in two different policies, **Kratos** detects a restriction conflict in the system. By incorporating these with hard, soft, and restriction conflicts, **Kratos** overall implements five distinct conflict types (more details in Appendix C).

**Policy Generation Module.** The goal of the policy generation module is to construct valid policies that reflect the demands and restrictions of all authorized users based on the device policies generated in the user interaction module. The generated policies are passed to the back-end module and stored in a database. Thereafter, these policies are enforced in smart devices.

**Access Control Rule Generation.** The negotiated policies computed by the policy negotiation algorithm are converted into enforceable access control rules. The negotiated policy clause, \( \Psi = \{ P, U, D, C, A \} \), has a 5-tuple format and is indeed well suited for existing attribute-based access control (ABAC) systems. Thus, **Kratos** uses an ABAC-like enforcement for the final generated rules. Here, the policy, \( B \), is the set of \{action, subject, resource, constraints\} tuples for a negotiated smart home policy. As an example, Figure 6 illustrates a simple example where \( ABAC(\Psi) \) holds a direct translation of actions, subjects, resources, and constraints. We develop an ABAC-like rule generator that enforces the rules in a control
\[
ABAC(\Psi_i) := \{ B \mid \text{action}(B) = A_i \land \\
\text{subject}(B) = U_i \land \\
\text{resources}(B) = D_i \land \\
\text{constraints}(B) = T_C \}
\]

where

\[
T_C := \{ c \mid \text{c satisfies the same conditions of C in mapped attributes into ABAC policy} \}
\]

Figure 6: An example of mapping a sample policy to ABAC rule through a transformation function. \( ABAC(\Psi_i) \) is a translation of action, subject, resources, constraints defined in a policy.

device. The generator is integrated into the hub device as a unified enforcement point.

4.4 Policy Execution Module

Policy execution module enforces the final policies generated from the policy negotiation process. Smart home devices can be controlled through a mobile phone controller app or by installing different device-specific apps in the system (e.g., Samsung SmartThings). Policy execution process appends the generated policies in the smartphone controller app or the installed smart home apps. To append the policies, KRATOS adds conditional statements to the app source code to enforce the policies. When a user tries to change the state of the device, the app asks the policy execution module to check in the policy table generated by a policy generator. If an acceptable condition is matched, the policy execution engine returns the policy to the app and creates a binary decision (true for the accepted policy and false for the restricted policy) in the conditional branches. Based on the decision enforced by the policy execution engine, the user command in a smart home app is executed. An example of KRATOS-modified app is presented in Appendix A.

5 KRATOS Implementation

We implemented KRATOS in Samsung SmartThings platform. We choose the SmartThings platform because of its large market share in consumer IoT and open-source apps [14]. We next provide details of our implementation.

Implementation and Data Collection. We setup a smart home environment to test the policy generation and negotiation process of KRATOS. We used Samsung SmartThings hub and connected multiple smart devices and sensors to the hub. The complete list of devices in our smart home environment is provided in Appendix D. The setup included four different types of devices: smart light, smart lock, smart thermostat, and smart camera, which are some of the most common smart home devices used in smart home settings [37]. We also used three different types of sensors: motion, temperature, and contact sensors to provide autonomous control.

In our implementation phase, we collected data from 43 different smart home users. We grouped our participants in 14 different groups and asked them to choose different roles in a smart home system. We investigated several multi-user scenarios for the policy generation and negotiation processes as detailed below:

Scenario 1: Multiple policies for the same device. We selected common devices (e.g., smart thermostat) and enforced different policies set by multiple users. Users assigned different demand and restriction policies in the system for the same device. We collected 14 sets of policies (a set of policy includes at least two policies from different users) which included three hard conflicts, seven soft conflicts, and two restriction conflicts.

Scenario 2: Multiple policies for different devices. We used multiple devices from the same device category (e.g., smart light, smart lock, smart camera, and smart thermostat) to enforce different policies over the same type of devices. Here, we collected 38 sets of policies from 43 users which resulted in eight hard conflicts, 18 soft conflicts, and five restricted user policies.

Scenario 3: Multiple apps for the same device. In the smart home system, we allowed multiple users to install different apps to control the same device (e.g., smart light). For example, multiple users can configure a smart light with both motion and door sensors using different apps. We chose three different smart light apps available in SmartThings market-
place (light control with the motion sensor, light control with the door sensor, and light control with luminance level) and asked the users to install preferable apps and assign device policies accordingly. Here, we collected 25 sets of policies including five hard conflicts, 12 soft conflicts, and three restriction conflicts.

**Scenario 4: Single app for multiple devices.** We considered an individual app controlling multiple same types of devices in the smart home environment. We chose a single light controlling app to control four different lights and asked users to enforce device policies in different devices using one single app. We collected 12 sets of policies in this scenario which includes two hard conflicts, four soft conflicts, and two restriction conflicts.

**Scenario 5: Temporary users in the system.** We considered a temporary user is added in the system and trying to access a smart light and smart lock after the access is expired for that specific user. We collected 10 sets of policies in this scenario.

**Malicious scenarios.** We also implemented five different threats in our smart home setup presented in Table 1. For Threat-1, we asked the users to add restriction clauses to the smart thermostat and asked the restricted users to change the temperature. For Threat-2, we asked a newly added user with lower priority to install a new app in the smart home and trigger a smart camera. Threat-3 is presented by a scenario where a new user changed the lock code of a smart lock and removed the smart lock from the environment. For Threat-4, we added a temporary authorized user with limited priority and asked the users to control a smart thermostat outside their accepted time range. For Threat-5, we asked the user with lower priority to add a new user with higher priority in the system.

**User Interface.** We built a SmartThings app that represents the user interaction module described in Section 4. This app has two modules: user management and policy management. The user management module allows users to add new users and assign priorities. We define five different roles and priority levels in Kratos (i.e., father/owner - priority 0, mother/owner - priority 0, adult - priority 1, child - priority 3, and a guest - priority 4). These roles and priorities can be assigned by the smart home owner or by authorized users with the same or higher priority to the one being assigned. Upon created a new role/priority, the information is sent and stored in the backend server. In the policy management module, users select devices and create new policies. Kratos provides options to add either general device policies (intended for all existing users) or policies that apply only to specific users. Kratos allows users to use different device conditions (operation-based, time-based, value-based, etc.) to define the policies. As our implementation environment had devices that only allows time-based and value-based conditions, we classified the policies in three different possible categories: (1) time-based device policy, (2) value-based device policy, and (3) time-value-based policy. The policies for different devices in our implementation can be represented by the following device policy array:

\[ \text{Device Policy, } P = \{U, D, C_1, C_2, R\}. \] (1)

The elements of the policy array are explained below.
- **User ID (U):** The first element of the policy array is to identify the policy assignee. We utilized the user email as a personal identifier in our implementation.
- **Device ID (D):** SmartThings assigns a unique device ID for each installed device which was used to identify the intended device for the policies.
- **Time conditions (C_1):** Users could assign a start time and an end time for any device action in the policies. For example, a smart light can be accessed from sunset to sunrise only.
- **Value conditions (C_2):** Users could assign a maximum and minimum value to specify an acceptable range to control a device functionality. For example, a user can set the operational range of a thermostat from 68°F to 70°F.
- **Restricted User (R):** High-priority Users could define the restriction policy for a specific lower-priority user by adding the user ID to the restricted user’s list. Users could also assign general policies (Section 2.3) for the devices by assigning ‘0’ in this field.

Figure 7 shows the user interface of Kratos. The information of new users and device policies are forwarded to the policy generator via the backend server for generating final device policies. Once finalized, the outcome of the policy generator is sent back to the user interface in the form of push notifications. The notifications inform the user when a policy is successfully generated or the reason why the policy generator failed why creating a new policy.

**Policy Enforcement.** The final step during implementation is to enforce the generated policies by Kratos. We utilized 10 different official SmartThings apps that control 17 different devices and installed them in the system. We installed all the apps and observed the user-specific policies generated in the policy generation module. We modified these apps to connect with the backend server and capture the generated policies from the policy generator. These policies were appended to the conditional statements inside the app to execute the policies. A sample modified app is given in Appendix 10 to illustrate the steps to enforce policies in a SmartThings app.

## 6 Performance Evaluation

In this section, we evaluate the efficacy of Kratos in implementing multi-user access control in a real-life smart home system. As explained in Section 5, we implemented Kratos in a SmartThings platform with multiple authorized users in the system. We evaluate Kratos by focusing on the following research questions (RQ):

**RQ1** How effective is Kratos in enforcing access control in multi-user scenarios while handling different threat models? (Sec 6.1)

**RQ2** What is the overhead introduced by Kratos on the normal operations of the smart home system? (Sec. 6.2)

### 6.1 Effectiveness

In this sub-section, we present the experimental results of Kratos while enforcing access control in different multi-user
Table 2: Different usage scenarios and outcomes of Kratos.

| Conflict type         | Policy example                                                                 | Kratos outcome                                                                 |
|-----------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Hard priority conflict| Alice (priority-1) and Bob (priority-2) set up the temperature range 60-70 and 75-80 respectively in the smart thermostat. | As Alice has higher priority, Kratos sets the thermostat to 60-70 and notifies the users with the decision. |
| Soft priority conflict| Alice (priority-1) and Bob (priority-2) set up the temperature range 60-70 and 65-75 respectively in the smart thermostat. | * If Alice has the higher priority, Kratos sets the thermostat to 60-70 and notifies Alice with common range (65-70). * If Alice agrees with common range, Kratos sets the temperature range 65-70. |
| Hard competition conflict| Alice (priority-1) and Bob (priority-2) set up the temperature range 60-70 and 75-80 respectively in the smart thermostat. | * Kratos starts the negotiation with average range (67-75) and upon mutual agreement from the users set the range. * If the users fail to agree, Kratos notifies higher level user/admin to decide the policy. |
| Soft competition conflict| Alice (priority-1) and Bob (priority-2) set up the temperature range 60-70 and 65-75 respectively in the smart thermostat. | Kratos sets the temperature range 60-70 and notifies the users with updated policy. |
| Restriction conflict | Alice (priority-1) set the temperature range 60-70 and restrict Bob (priority-2) to change the thermostat. Bob sets the temperature range 75-80. | Kratos sets the temperature range 60-70 and notifies Bob regarding restriction. |
| Temporary access     | Alice (priority-1) added Gary (priority-4) as a temporary user for 2 days. After 2 days, Gary tries to unlock the smart lock. | Kratos automatically detects the expired validity for smart home access and deletes Gary from authorized user list to prevent any undesired access. |

We also evaluated the effectiveness of Kratos in preventing different threats in the smart home systems. We considered five different threats presented in Section 3, Table 1. The implementation detail is given in Section 5. We collected data from fifty malicious occurrences in total to evaluate Kratos against these threats. Table 4 summarizes the performance of Kratos in identifying different threats. In each of these scenarios, Kratos detected the policy violation with 100% accuracy and effectively notified the smart homeowner/policy assigner via push notifications. For Threat-1, Kratos achieves the lowest average detection and notification time 0.25 and 0.4 seconds respectively. To identify Threat-2 and 3, Kratos takes 0.4 and 0.47 seconds on average with average notification time 0.6 seconds. For Threat-4 and 5, the average detection time is 0.35 and 0.28 seconds, respectively. In summary, Kratos can detect different threats with 100% accuracy and notify users with minimum delay.

6.2 Performance Overhead

In this sub-section, we present the performance overhead of Kratos in a multi-user smart home system. Here, we considered the following research questions while measuring the performance overhead of Kratos:

- **RQ3** What is the impact of Kratos in normal operations of the smart home system? (Table 5)
- **RQ4** What is the impact of Kratos in executing a user command in the smart home system via the smart home apps? (Table 6)
- **RQ5** How does the impact of Kratos change with different parameters in the smart home environment? (Figure 8)

For different multi-user scenarios, we considered four different scenarios as explained in Section 5.

**Latency Introduced by Kratos.** Kratos considers three different types of conflicts (hard conflicts, soft conflicts, and restriction policy) during policy generation and negotiation based on user priorities and policy types. These policy generation and negotiation processes normally introduce latency in evaluated 48 sets of policies in total with an average policy generation time of 1.2 seconds. In Scenario-3 and 4, Kratos manages 35 and 32 sets of policies with an average generation time of 0.86 and 0.48 seconds respectively. In Scenario-5, Kratos successfully manages 10 sets of policies and automatically detects unauthorized access for expired temporary access. Kratos also successfully resolves all the conflicts generated in different scenarios. In summary, Kratos successfully resolved the policy conflicts and created optimized final policies that could be executed within different smart home apps.

Table 3: Summary of Kratos’s performance in different scenarios.
Table 4: Performance of Kratos in detecting different threats. The normal operations of a smart home system and the smart apps to analyze given policies and solving conflicts. Table 5 illustrates the delay introduced by Kratos while handling the policy conflicts and negotiations. We note that the average negotiation time increases with the number of policies for all types of policy conflicts. For hard conflicts, the average negotiation time is 0.403 seconds for ten policies, which increases to 1.21 seconds for 30 policies. Because the hard conflicts require all the conflicted users to interact with the system to resolve the conflicts, it takes more time than soft conflict and restriction policies. For soft conflicts, the average negotiation time is 0.27 seconds for ten policies which increases to 0.73 seconds for 30 policies. For the restriction policies, the latency is introduced only when a low-priority user tries to assign policies to high-priority users. In this case, average negotiation times vary from 0.102 seconds to 0.25 seconds from 10 to 30 policies.

Table 5: Overhead of Kratos in handling policy conflicts and negotiations.

Impact of Kratos on Executing User Commands. As the policies in Kratos are enforced in the smart apps installed via the controller device (e.g., smartphone and smart tablet), it introduces overhead in the controller devices while installing the apps and executing users’ command. Table 6 depicts the impact of Kratos on executing user commands based on generated policy. Here, we used eight different apps to measure the performance overhead of Kratos. We also considered three types of constraints on the policies: time constraint, value constraint, and both time and value constraints. Time constraint refers to the specific time range for the desired action of a smart device (e.g., turning on lights at sunset) while value constraint refers to the specific range of inputs to a smart device (e.g., the temperature of the smart thermostat). With no policy enforced on a device, the average time to install an app and execute user command is 1.3 seconds with 1.75% and 1.6% of CPU and RAM utilization, respectively. For time constraints and value constraints, the average time is 1.72 and 1.46 seconds, respectively. Average CPU and RAM utilization are almost similar for both time and value constraints (2.1-2.2% and 2.25-2.6%, respectively). For both time and value constraints, the average execution time increases to 1.92 seconds. The CPU and RAM utilization also increases to 2.5% and 2.82%, respectively. Considering the CPU and RAM available in modern smartphones and tablets, the overhead introduced by Kratos can be considered negligible [33, 34].

Table 6: Overhead of Kratos in policy executions.

Impact of Different Parameters on Performance Overhead. Kratos considers different parameters in smart home systems to define and execute device policies reflecting diverse user demands. Here, we observed the performance overhead of Kratos by changing various parameters. As policy generation and negotiation are executed at the backend server, Kratos does not pose any performance overhead to computational parameters (CPU and RAM utilization). The only noticeable change is observed in delay imposed by Kratos in the normal operation of the smart home system. In Figure 8, the delay introduced by Kratos is shown based on the number of policies, conflicts, users, and devices. One can notice from Figure 8a, the delay introduced by Kratos increases with the number of policies generated by the users. Kratos introduces 90 ms delay in the smart home system for five policies to execute a user command which increases to 280 ms delay for 60 policies. The delay increases linearly with the number of conflicts and users in the system (Figure 8b and Figure 8c). The highest delay to execute a user command is 368 ms, which occurs when the system includes 30 dif-

Figure 8: Impact of different parameters on Kratos: (a) number of policies, (b) number of conflicts, (c) number of users, and (d) number of devices.
different policy conflicts. K\textsc{ratos} also takes 310 ms to execute a command with six different users present in the system. This delay is the result of the overhead introduced by notifying different users about executing the command. For the number of devices, the delay introduced by \textsc{kratos} becomes steady after adding 12 different devices in the smart home system (Figure 8d).

7 Usability Study

To understand the usability of \textsc{kratos} among users, we also performed a second usability study with 43 smart home users. Again, although it is not the primary goal of this work, it is important to understand the users’ perspectives on the usability effectiveness of \textsc{kratos}. Again, we obtained Institutional Review Board (IRB) approval and we gave monetary compensation to the users to test our proposed access control system. In this study, users experienced the proposed access control system in a real-life smart home environment supported by Samsung SmartThings. We created SmartThings app for \textsc{kratos} and made it available to the users to install and use it to add new users, add demand policies, add restriction policies for specific users, and experience policy conflict resolution provided. More details of the questions included in the usability survey are provided in Appendix F. The questions included in the usability study were divided into three different categories:

• Installation and tutorial: In this part, users were asked to install the \textsc{kratos} app in the system and learn how to use \textsc{kratos} in the smart home systems.

• Policy enforcement and notification system: In the second part of the usability test, users were asked to create different types of policies (demand and restrict policy) using \textsc{kratos} and experience the notification system implemented in \textsc{kratos}.

• Policy conflict and implementation: In the last part, users experience the conflict resolution of \textsc{kratos} and observe the implemented policies in the system.

In the following, we summarize the findings of the usability study and discuss how users took \textsc{kratos} in a smart home system. A summary of the study is given in Table 7.

| Category               | Rating       | Category                | Rating       |
|------------------------|--------------|-------------------------|--------------|
| User interface         | ★★★★★       | Processing time         | ★★★★★       |
| Tutorial               | ★★★★★       | Policy generation       | ★★★★★       |
| Installation process   | ★★★★★       | Conflict resolution     | ★★★★★       |
| Notification system    | ★★★★★       | User restriction        | ★★★★★       |
| Availability           | ★★★★★       | User-friendly           | ★★★★★       |
| Ease                   | ★★★★★       | Effectiveness           | ★★★★★       |

Table 7: Summary of the usability study of \textsc{kratos}.

Installation and tutorial. 95.3% of the users installed the app successfully using the instructions provided in the app and 97.7% of the users thought the provided tutorial was adequate to operate the app and perform different functions successfully. In terms of device availability for policy enforcement, \textsc{kratos} scored 5 on a scale of 5.

Policy enforcement and notification system. In terms of priority assignment, 93% users understood and correctly added new users in the system. For assigning demand policies, 100% of the users successfully enforced and understood the notifications correctly. 97.7% users understood the notification messages clearly.

Policy conflict and implementation. In this part, users experience how \textsc{kratos} implemented the generated policies in the system and resolve conflicts between different user demands. Finally, the 97.7% of users were satisfied with the demand policy decisions generated by \textsc{kratos} while 100% of the users were satisfied with the restriction policy decisions.

8 Benefits and Future Work

Consider a user, Bob, who defines himself as a technology savvy person and owns a smart home. The home is set with devices such as smart lock, thermostat, fire alarm, and smart coffee maker. Bob’s is the head of a family of three members, including his wife Alice, and his teenage son Matt. Finally, Bob is an enthusiastic entrepreneur that offers high-quality vacation rentals to Airbnb users.

Efficient Conflict Resolution. With several devices shared among all household members (including the Airbnb tenant), Bob feels that there is an immediate need for some control mechanism that defines how all the smart devices are being set up and managed among the different users. However, despite trying devices and smart apps from different platforms (e.g., Samsung SmartThings, Google Home, etc.), Bob cannot find a feasible and user-friendly solution that consider the needs of the different users (e.g., Bob and Alice’s priority is to keep the thermostat temperature as high as possible while Matt’s idea is to have cooler temperature). \textsc{kratos} offers an access control mechanism for the SHS that allows Bob to provide access control based on the users’ needs and priorities.

Multi-users/Multi-devices. As mentioned before, Bob’s setup comprises several different devices with different levels of usability based on their impact on the quality of life of users and their contribution to the general protection and security of the household. Additionally, different users may have different levels of access based on Bob’s and the household’s best interests. Based on these scenarios, Bob expects an smart home access control system capable of managing multi-user and multi-device environments. \textsc{kratos} realizes and offers an access control system where the administrator (i.e., Bob) can assign priority levels to the different devices and users. This allows control mechanisms that consider the importance of the various devices, but also the needs of the users based on admin’s pre-defined priorities.

Suitability for Complex User Demands. Users’ demands can be very complex at times. For instance, in addition to the demands and interests of Bob, Alice, and Matt, new access control policies can be generated in case Bob decides to give some control to his Airbnb tenant Ed. Adding new users and devices to an already configured system increase the complexity due to new conflicts between users and policies. To solve these issues, \textsc{kratos} can actively analyze and solve policy conflicts through negotiations in an optimized fashion based on the different user and device priorities.

Inherent Security. Bob has certain rules to protect his ecosys-
tem. First, security-related devices (e.g., smart lock) have the highest priority. Second, he would like to have strict and unique control over these devices, so no other user can change their settings or expected behavior. Finally, users with the lowest priority (e.g., Ed) should not be able to add new devices, change SHS settings, etc. Our framework was designed to provide inherent security based on the specific user’s needs. Specifically, KRATOS offers the means to provide complex control and demands through comprehensive policy negotiation and conflict resolution.

**Intuitive and Easy User Interaction.** Finally, Bob desires a user-friendly tool, especially because some users with little technical knowledge may need to interact with the new access control system. KRATOS addresses all the steps from gathering users’ declared demands and policies to access control enforcement with minimal user interaction. For this, our framework learns from the different priorities from users and devices to create efficient and fully automated policy conflict resolution mechanisms.

**Encrypted Sensitive Data.** KRATOS accumulates user preferences, device usage, and connected users’ credentials which can be considered as sensitive data. These data should be encrypted to ensure privacy of the users. KRATOS is implemented in Samsung SmartThings which uses encrypted communication channels between smart home devices and the controller devices (smartphone, tablets, etc.). Furthermore, we used encrypted cloud space (Google Cloud) to store the user priority list and generated device policies to ensure user privacy in KRATOS.

We implemented KRATOS in Samsung SmartThings platform. Although it is a widely-used platform with the largest market share, we aim to extend KRATOS by considering a platform-independent implementation. There are different smart home platforms available in the market and none of the existing platforms offers fine-grained access control system [16]. In the future, we will implement KRATOS in different smart home platforms and test its effectiveness.

| Prior Work | Domain | Multi-user multi-device environment | User interface | User conflict resolution | Overhead analysis | Access control language | Usability study | User study |
|------------|--------|------------------------------------|----------------|-------------------------|------------------|------------------------|----------------|-----------|
| xShare [20]| Smartphone | ○ | ● | ○ | ○ | ○ | ● | ● |
| DiffUser [25]| Smartphone | ○ | ● | ○ | ○ | ○ | ○ | ○ |
| Capability-based access control [15]| IoT network | ● | ● | ○ | ○ | ○ | ○ | ○ |
| Situation-based access control [30]| Smart home | ● | ○ | ○ | ● | ○ | ○ | ○ |
| Expat [42]| Smart home | ● | ○ | ○ | ● | ● | ○ | ○ |
| Zeng et al. [44]| Smart home | ● | ● | ○ | ● | ● | ● | ● |
| KRATOS | Smart home | ● | ● | ○ | ● | ● | ● | ● |

Table 8: Comparison between KRATOS and other access control mechanisms for multi-user environment.

In both works, smart home users clearly raise their concerns regarding the need of access control mechanism in SHS. In addition, these studies also summarize several design specifications to reflect users’ needs in an access control mechanism. Matthews et al., also points out relevant issues with smart home users that share the same devices and accounts [23]. However, no explicit solution for multi-user access is proposed in any of these works.

In other works, researchers explore different access control strategies when multiple users share a single IoT device. Liu et al. suggested a user access framework for the mobile phone ecosystem called xShare, which provides policy enforcement on file level accesses [20]. Ni et al. presented DiffUser, a user access control model for the Android environment based on access privileges [25], which is only effective for a single device. Tyagi et al. discussed several design specifications needed for multi-party access control in a shared environment [40]. Aside from these works, there are few prior proposing access control systems for multi-user multi-device SHS. Gusmeroli et al. suggested a capability-based access control for users in a multi-device environment [15]. However, this system is not flexible enough to express the real needs of the users. Jang et al. presented a set of design specifications for access control mechanism based on different use scenarios of multi-user SHS [18]. Schuster et al. proposed a situation-based access control in the smart home system which considers different environmental parameters [30]. Here, the authors considered state of the device along with the location of the users to determine a valid access request. However, this work does not solve the conflicting demands of multiple users. Yahyazadeh et al. presented Expat, a policy language to define policies based on user demands [42]. In a recent work, Zeng et al. built an access control prototype with different access control options for smart home users [44]. Here, the authors considered four different access control mechanisms and assessed in a month-long user study among seven households to understand the users’ needs and improve the design. However, they did not implement the framework in real-life systems and did not consider user conflicts while operating in a multi-user smart environment.

**Differences from existing works.** KRATOS presents a usable fine-grained access control system designed for multi-device multi-user smart home scenarios that reflects feedback obtained from a user study. KRATOS offers easy new-user addition with priority levels that considers device restrictions for specific users and automatic policy negotiation for conflicts. In addition, KRATOS provides easy policy assignment and management capabilities for multiple users. Table 8 summarizes...
the differences of Kratos and other existing solutions.

10 Conclusion

In a smart home system (SHS), multiple users have access to multiple devices simultaneously. In these settings, multiple users may want to control and configure the devices with different preferences which give rise to complex and conflicting demands. In this paper, we explored the need of fine-grained access control mechanism in smart home systems and developed Kratos, an access control system that addresses the diverse and conflicting demands of different users in a shared multi-user smart home system. Kratos implements a priority-based policy negotiation technique to resolve conflicting user demands in a shared smart home system. We implemented Kratos on real-life settings and evaluated its performance through real devices in a multi-user setting. Kratos successfully covers the users’ needs, and our extensive evaluations showed that Kratos is effective in resolving the conflicting requests and enforcing the policies without significant overhead. Also, we tested Kratos against five different threats and found that Kratos effectively identifies the threats with high accuracy.

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We evaluated the effectiveness of Kratos by enforcing policies in Samsung SmartThings Apps. We selected eight Apps to enforce Kratos generated user policies and appended the policies inside the App. Here, we give an example of Kratos-enabled official SmartThings App.

### Listing 1: Policy enforced at install time

```python
import groovy.time.*
definition{
    name: "Big Turn ON modified",
    namespace: "smartthings",
    author: "Anonymous",
    description: "Turn your lights on when the SmartApp is tapped or activated."
}
category: "Convenience",
iconUrl: "https://s3.amazonaws.com/smartapp-icons/Meta/light_outlet.png",
icon2xUrl: "https://s3.amazonaws.com/smartapp-icons/Meta/light_outlet@2x.png"
}

preferences {
    section("When I touch the app, turn on...") {
        input "switches", "capability.switch", multiple: false
        input name: "email", type: "email", title: "Email!", description: * Enter Email Address * required: true,
        displayDuringSetup: true
    }
}
def installed()
    { ...
        atomicState = { ...
            if (atomicStateSmartLightTimes == []) ...
            listTimes.add (atomicStateSmartLightTimes)
        }
    }
def updated()
    { ...
        atomicState = { ...
            if (atomicStateSmartLightTimes == []) ...
            listTimes.add (atomicStateSmartLightTimes)
        }
    }
}
```

A Kratos enforced in a Samsung SmartThings App

We evaluated the effectiveness of Kratos by enforcing policies in Samsung SmartThings Apps. We selected eight Apps to enforce Kratos generated user policies and appended the policies inside the App. Here, we give an example of Kratos-enabled official SmartThings App.

**Listing 1: Policy enforced at install time**
B Policy Negotiation Algorithm of KRATOS

During policy negotiation, each policy clause is compiled into a quintuple, $\Psi = \{P, U, D, C, A\}$, where $P$ is the policy assigner (that shows who states this clause), $U$ is the assignee (about whom this statement is), $D$ is the targeted smart device, $C$ is a set of conditions over $D$ and $U$, and configurable environmental attributes, and finally $A \in \{\text{demand, restrict}\}$ is the action requested by this statement when the set of conditions are satisfied. KRATOS implements an algorithm to solve the policy conflicts through a set of equations as follows:

$$interfere(\Psi_i, \Psi_j) \leftarrow U_i = U_j \land D_i = D_j$$

$$hard\_conflict(\Psi_i, \Psi_j) \leftarrow interferes(\Psi_i, \Psi_j) \land (A_i \neq A_j \land \forall c \in C : \Theta(\Psi(c), C_i, \Psi(c), C_j))$$

$$soft\_conflict(\Psi_i, \Psi_j) \leftarrow interferes(\Psi_i, \Psi_j) \land (A_i = A_j \land \forall c \in C : \Theta(\Psi(c), C_i, \Psi(c), C_j))$$

$$HPC(\Psi_i, \Psi_j) \leftarrow hard\_conflict(\Psi_i, \Psi_j) \land \Xi(P_i) \neq \Xi(P_j)$$

$$SPC(\Psi_i, \Psi_j) \leftarrow soft\_conflict(\Psi_i, \Psi_j) \land \Xi(P_i) \neq \Xi(P_j)$$

$$HCC(\Psi_i, \Psi_j) \leftarrow hard\_conflict(\Psi_i, \Psi_j) \land \Xi(P_i) = \Xi(P_j)$$

$$SCC(\Psi_i, \Psi_j) \leftarrow soft\_conflict(\Psi_i, \Psi_j) \land \Xi(P_i) = \Xi(P_j)$$

$$RC(\Psi_i, \Psi_j) \leftarrow Restriction\_conflict(\Psi_i, \Psi_j) \land \Xi(P_i) > \Xi(P_j) \land A_i = restrict$$

where $\Psi_i, \Psi_j$ is the evaluated pair of policies, and $\Psi'(c, C)$ is the value function that returns the value of conditional $c$ in the set $C$, $\Theta(x, y)$ checks the overlap between the provided $(x, y)$ tuple and $\Xi(u)$ returns the priority of user $u$ as the value of user’s assigned priority class.

C Policy Negotiation Process in KRATOS

The negotiation $\mathcal{A}$ between two given policy clauses $(\Psi_i, \Psi_j)$ can be formally expressed and computed by a sample function as in Equation 9.

$$\mathcal{A}(\Psi_i, \Psi_j) = \begin{cases} \Psi_i & \text{if } \Xi(P_i) > \Xi(P_j) \\ \Psi_j & \text{otherwise} \end{cases}$$

$$\text{if } HPC(\Psi_i, \Psi_j)$$

$$\text{if } SPC(\Psi_i, \Psi_j)$$

$$\text{if } HCC(\Psi_i, \Psi_j)$$

$$\text{if } SCC(\Psi_i, \Psi_j)$$

In the case of a hard priority conflict (HPC), (e.g., mother vs. child with contradicting clauses) KRATOS prioritizes the clause of the user with the higher priority (e.g., mother). For hard competition conflict (HCC), both users with overlapping conditions are notified and KRATOS offers a common operating condition to both. This common condition is enforced as a policy to the device upon users’ agreement. On the other hand, in the case of both soft priority (SPC) and soft competition conflicts (SCC), the result of the negotiation is a new clause with common set of conditions. For restriction conflict, both restricted user and policy assigner are notified and if the policy satisfies conditions in Equation 9, the restriction policy is enforced in the device.

D Devices Used During Evaluation

We present a detailed list of devices used during the implementation and evaluation of KRATOS in Table 1.

| Device Type       | Model                                | Quantity |
|-------------------|--------------------------------------|----------|
| Smart Home Hub    | Samsung SmartThings Hub              | 1        |
| Smart Light       | Philips Hue Light Bulb               | 4        |
| Smart Lock        | Yale BTL Lock with Z-Wave Push Button Deadbolt | 1 |
| Smart Camera      | Arlo by NETGEAR Security System      | 1        |
| Smart Thermostat  | Ecobee 4 Smart Thermostat           | 1        |
| Motion Sensor     | Fibaro FGMS-001 ZWS Motion Sensor with Z-Wave Plus Multisensor | 6 |
| Temperature Sensor| Fibaro FGMS-001 ZWS Motion Sensor with Z-Wave Plus Multisensor | 1 |
| Door Sensor       | Samsung Multipurpose Sensor          | 2        |

Table 1: Devices and sensors used in our smart home setup to evaluate KRATOS.

E User Study Example Questions

We presented a representative set of questions from all the categories. The full set of questions can be found at https://anonymous-user.com.
E.1 User Characterization

1. While using/installing a smart home device, did you have to consider suitable settings for other users in your home?
   ( ) Yes
   ( ) No

2. While using a smart home device, do you have to change device settings each time other users change the setting?
   ( ) Yes
   ( ) No

E.2 Smart Home Setting Preferences

1. Do you think current smart home platforms should provide an integrated access control system?
   ( ) Yes
   ( ) No
   ( ) Maybe

2. In order to provide access control, would you be willing to install and use a separate app in addition to the traditional app controlling the devices?
   ( ) Yes and I am willing to use and pay for the service, if there is a fee
   ( ) Yes if the app is free and trusted
   ( ) Maybe
   ( ) No, because it is too much hassle
   ( ) No, because I don’t need access control

E.3 Multi-user multi-device scenarios

1. In your smart home, you and your parent/partner/roommate has the same level of priorities. Both of you want to change the setting of a device in different ways. Do you think an automatic negotiation system would help you to solve this?
   ( ) Yes
   ( ) No

2. You already have a policy for a device in the access control system. You want to modify the previous policy and enforce a new policy. Do you think an access control system should have this function?
   ( ) Yes
   ( ) No
   ( ) Maybe

E.4 User Study Detailed Results

The survey was divided into three main blocks of questions:

• Block 1 – User Characterization: The first group of questions focused on characterizing the users. With this, we aimed to understand the needs and interest of a diverse group of users.

• Block 2 – Smart Home Setting Preferences: The second set of questions aimed to characterize the user’s smart home setting preferences. We asked questions to characterize (1) users’ need for access control systems and (2) their expectations about how it should be implemented.

• Block 3 – Multi-user/Multi-device Scenarios: Finally, we asked questions about general multi-user and multi-device settings. The goal of these questions is to get feedback from the users regarding how different conflicts, policy negotiations, and devices with different priorities should be handled.

In the following, we present the survey’s results and discuss how Kratos addresses the needs of users in each case.

E.5 User Characterization

We surveyed a total of 72 users. We fully characterize the group of users and their households, after processing answers grouped in the following five topics:

Age: Out of 72 participants, 31.9% users reported ages in the range of 15-24 years, 56.9% users were in the range of 25-34 years, and 11.1% in the range of 35-44 years.

Smart Device Usage: 80.6% of the surveyed users stated that they either have used or had some smart home device in their homes.

Smart Home Device Types: We also asked users about the device types they had. The most popular devices among the surveyed users were: Smart TV 68.1%, smart light 38.9%, smart thermostat 23.6%, smart camera 22.2%, smart lock 22.2%, and smart switch 15.3%.

Smart Home Platforms: Out of 10 different smart home platforms included in the survey, the users stated that they were mostly familiar with four smart home platforms: Google Home 93.1%, Samsung SmartThings 55.6%, Apple HomeKit 48.6%, and OpenHAB 9.7%. Further, we asked details about the specific smart home platform that they actually (or were willing to) used. Similar to the previous results, Google Home, Samsung SmartThings, and Apple HomeKit were the majority of the answers, 50%, 18.1%, and 16.7%, respectively.

Technical Experience: We also surveyed the users regarding their technical experience with smart home devices and Apps. Out of the total, 79.2% of the users reported that they knew how to set up smart devices, 52.8% stated that they knew how to install apps, and 47.2% said that they felt comfortable integrating different smart home devices using a hub or cloud.

Household Characteristics: Finally, we asked questions regarding the household characteristics. For instance, 44.4% of the users stated that they lived in a size of 4, 22.2% reported living in a size of 3, and 15.3% of users shared their spaces with at least another person. The remaining users lived in a family size of 5 or higher. Further, we asked about how many members of these households shared smart devices. Interestingly, only 19.4% reported that they did not share deployed smart devices with anyone else. Then, out of the users remaining, 70.9% of them disclosed that they shared devices with at least two more household members and up to 7.
We used the answers obtained in this block of questions to characterize the target user ofKRATOS. In most cases, users of smart home devices and apps know how to configure devices and install apps. Additionally, multi-user smart households represent a positive potential environment for multi-user access control systems likeKRATOS. Finally, we note that most of the users reported that they share a smart device with at least two other household members.

E.6 Smart Home Preferences and Characterization

We also asked questions to the users about access control features in a smart home setting as follows:

Multi-member Settings: We asked users if they had ever considered a need for defining various controls on the other users while installing or using smart apps. In total, 61.1% users answered “Yes” to this question.

Multi-member Access: Further, we investigated if the users were ever had given device accesses to other members. In this case, a higher majority of 70.8% users answered “Yes”.

Conflicts Among Settings: In multi-user scenarios, 36.1% surveyed users disclosed having to update or re-evaluate smart device settings after discovering that original settings had been changed/modified by other members of the household that had authorized access to the devices.

Multi-member Admin Interface: Regarding the multi-member scenarios, 86.1% of the users agreed that smart home apps should have an interface that can be regularly checked by the device owner to control the access rights of devices.

Guest Access: Lastly, we asked about giving device access to guest members (visitors, tenants, etc.). A vast majority of users 88.9% responded “Yes” to the option of smart Apps having an automated mechanism to revoke access requests from guest users.

Overall, these set of questions shows the need for access control mechanisms in smart home systems. We found that the device owners frequently had to deal with conflicts as a result of settings changed by other members of the household. Additionally, the device owner wanted to have control regarding who accesses the devices and desired to enforce limited access controls for the users that are not fully trusted.

E.7 Multi-user/Multi-device Access Control

We assess the need for access control mechanisms, and feedback of users on the design and implementation of such mechanisms.

Integrated Access Control: We asked the users whether they thought an access control mechanism should be provided in smart home scenarios. A majority of 80.6% of users answered that it would be an essential feature and smart home platforms should provide an integrated access control system.

Separated Access Control: We further asked whether there is a need for a separate app/system to manage the access control. Surprisingly, 80.5% users positively answered. Out of the total, 59.7% users desired to use an access control application if it were free and secure, while 20.8% stated that they might even pay for the service. Additionally, the users agreed to share some specific personal information (PI) with the access control app if required for the app design. Out of 6 different options provided, the users stated that they would allow the app to use their email address 70.8%, smart home user ID 63.9%, smart home account credentials 54.2%, and smart device ID 52.8%.

Member Priorities: We asked the users about who in the household should have the highest priority (the most trusted member) and the lowest one (the least trusted member). The users assigned priorities levels in between these boundaries. The “spouse/partner”, “father”, and “Mother” are among the members with the highest priorities. On the contrary, “babysitter”, “temporary guest”, “frequent visitor”, and “cleaning personnel” were among the members that had the lowest priority.

Device Priorities: We evaluated what type of devices should be included in the access control mechanism. Out of 18 options, the devices related to security and safety were selected to be the most important devices for access control. This list includes devices such as smart lock, smart thermostat, smart fire alarm, smart monitoring system, presence sensor, and smoke sensor. On the other hand, devices with the least importance to the user were the smart coffee machine, doorbell, and smart Light.

Automated System: 69.4% users answered positively to the possibility of having an automated negotiation system to solve access control conflicts among members with the same level of priority.

Update Policy Feature: 76.4% users expressed their interest in having a feature to update/change current access control policies.

Negotiation Process: We presented four different options regarding how the policy negotiation process should work among users of the same priority. The answer of users shows that users desire to automate this process with minimal interaction 51.4%. The users’ answers also suggested that the access control system should notify the members affected by the policy conflict.

Multiple Policies: The users reported that the access control system should allow multiple policies when a conflict occurs. 69.4% users suggested that a simple notification and an automated approval of the non-conflicting policies are sufficient.

Conflicting Policies: If two policies conflicts and one of them is defined from a member with lower priority, 44.4% of users suggested that the lower priority policy should be rejected. However, 38.9% users indicated that the member with the higher priority should be asked about reconsidering her policy to avoid conflict. In both cases, they again suggested that a notification system is a critical feature to resolve policy conflicts. Further, we presented a situation where a member that had the same priority level as the owner introduces a conflicting policy on behalf of a low-priority member. In this scenario, 56.9% users suggested that both the owner and the member with similar priority should be notified so that they
can negotiate together how to solve the conflict. However, 25\% users proposed that the high-priority member should be notified about the conflict with the owner and the new policy should be automatically rejected.

**Low-Priority Members:** The last two questions were about managing the low-priorities members. The majority of the users 65.3\% confirmed that the access control system should have a feature to monitor the actions and settings from low-priority members while other 25\% suggested that this may be an additional feature to have. We obtained similar results when we specifically asked about access control for guest members. In this case, 72.2\% surveyed users replied that guest members needed to have some kind of restrictions while other 19.4\% users said that this would be an additional feature to include.

**F Usability Instrument**

We present a representative set of questions from all the categories. The full set of questions can be found at https://anonymous-usability.com.

**F.1 Installation and Tutorial**

1. Does the app provide an organized and easy to follow user interface?
   - Yes
   - No

2. On a scale of 1 to 5 (1 being too hard to follow), how easy to understand the information provided via the notification(s) in Kratos?
   - 1
   - 2
   - 3
   - 4
   - 5

**F.2 Policy Enforcement and Notifications**

1. Does Kratos detect any invalid user in the system with no assigned priority and provide feedback via notifications?
   - Yes
   - No

2. On a scale of 1 to 5 (1 being too slow), how quick does Kratos notify users upon successful transaction?
   - 1
   - 2
   - 3
   - 4
   - 5

**F.3 Policy Conflict and Implementation**

1. In a smart home system, an admin might need to restrict the use of a specific device for some users. Does Kratos provide this option in policy enforcement?
   - Yes
   - No

2. On a scale of 1 to 5 (1 being really hard to use and 5 being user-friendly), how easy to install and use Kratos is?
   - 1
   - 2
   - 3
   - 4
   - 5