Systematically Ensuring The Confidence of Real Time Home Automation IoT Systems

Lei Bu, Wen Xiong, Chieh-Jan Mike Liang, Shi Han, Dongmei Zhang, Shan Lin, and Xuandong Li

Recent advances and industry standards in Internet of Things (IoT) have accelerated the real-world adoption of connected devices. To manage this hybrid system of digital real-time devices and analog environments, the industry has pushed several popular home automation IoT (HA-IoT) frameworks, e.g., IFTTT (If-This-Then-That), Apple HomeKit, and Google Brillo. Typically, users author device interactions by specifying the triggering sensor event and the triggered device command. In this seemingly simple software system, two dominant factors govern the system confidence properties with respect to the physical world. First, IoT users are largely non-expert users, who lack the comprehensive consideration regarding potential impact and joint effect with existing rules. Second, while the increasing complexity of IoT devices enables fine-grained control (e.g., heater temperature) on the continuous real time environments, even two simply connected devices can have a huge state space to explore.

In fact, bugs that wrongfully control devices and home appliances can have ramifications to system correctness and even user physical safety. It is crucial to help users to make sure the system they created meets their expectation. In this paper, we introduce how techniques from hybrid automata can be practically applied to assist non-expert IoT users in the confidence checking of such hybrid HA-IoT systems. We propose an automated framework for end-to-end programming assistance. We build and check the linear hybrid automata (LHA) model of the system automatically. We also present a quantifier elimination based method to analyze the counterexample found and synthesize the fix suggestions. We implemented a platform, MenShen, based on this framework and proposed techniques. We conducted sets of real HA-IoT case studies with up to 46 devices and 65 rules. Empirical results show that MenShen can find violations and generate rule fix suggestions in only 10 seconds.

CCS Concepts: •**Computer systems organization** → **Embedded and cyber-physical systems;** •**Software and its engineering** → **Model checking;**

Additional Key Words and Phrases: IFTTT, Home Automation, Internet of Things, Linear Hybrid Automata, Automatic Modeling and Verification, Fix Suggestion.

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1. INTRODUCTION

With the rapid advancement of computing technology, the computing paradigm of cyber-physical systems (CPS) [Lee 2006] has emerged in the last decade. Under this paradigm, sensor data can be acquired and processed in real time, which then drive intelligence [Lin et al. 2008]. Furthermore, riding on the momentum of Internet of Things (IoT), the industry has pushed for standards that enable more connected devices to interoperate. However, center to this connected vision is a IoT control framework, which manages the hybrid system of digital real-time devices and analog environments in a space. Many home owners have benefited from this IoT control framework. For example, they can author automation tasks that send the SMS message to the house owner when the kitchen has high smoke level.

The industry has pushed out several offerings of the home automation IoT (HA-IoT) service, e.g., IFTTT.com (If-This-Then-That) [ift 2011], Apple HomeKit [ah 2016], and Google Brillo [gb 2016]. Interestingly, the user base of home automation largely consists of non-expert users who have insufficient background with programming hybrid control systems. Therefore, these industry offerings simplify authoring an automation task down to authoring a set of intuitive event-triggered rules – or IFTTT-style rules. IFTTT rules are popular among HA-IoT services, and one HA-IoT service, IFTTT.com, has tens of thousands of active users and over 340,000 shared rules. An IFTTT-style rule is in the format of `if A then do B`, where `A` is a triggering sensor event and `B` is a triggered device command. We illustrate the automation task with an example of two rules, which regulates the CO concentration to be under 200 ppm in a space[1].

```
IF Smart_Fan.CO_reading == 195  THEN execute Alarm.TURN_ON command
IF Alarm.TURN_ON.Signal ==TRUE THEN execute Smart_Fan.ACTIVATE command
```

This CO example has a clear relation with the users' safety. There is also another widely used rule which concerns the user experience of keeping the room temperature in certain range and also concerns energy saving[2].

```
IF Room. Temperature_reading ==20 THEN execute HVAC.TURN_OFF command
IF Room. Temperature_reading ==28 THEN execute HVAC.TURN_ON command
IF HVAC.TURN_ON.Signal == TRUE THEN execute Window.CLOSE command
```

However, while individual IFTTT-style rules are simple to author, reasoning about their confidence (i.e, whether a system's real time behavior conforms to a user's expectation) is a complicated task with implications to the system confidence. This is crucial as wrongfully actuating IoT devices and appliances could have ramifications on user physical well-beings (e.g., high CO concentration). Such reasoning needs accurately modeling the behavior of a system of devices over the time domain. The challenges arise from the fact that (1) environment and system variables are changing continuously, (2) events can happen at any time, and (3) the number of interactions to inspect increases with the number of automation rules. More importantly, while typical real time control systems are maintained by domain experts, HA-IoT systems are operated by non-expert home users. Therefore, building on formal model checking, we investigate *new approaches and tools to help non-expert IoT users in systematically realizing high-confidence real time HA-IoT systems*.

Our system design is guided by two main principles. First, there is an increasing number of IoT appliances that deal with *real time continuous environments* with *dynamic laws* and *time delays*. In our CO example, if the smart fan is activated, it can

[1]We note that this CO concentration case is inspired by a rule uploaded by normal users on IFTTT.com, https://ifttt.com/recipes/368595-turn-on-your-air-purifier-when-the-air-quality-decreases.

[2]This HVAC case is also inspired by a rule on IFTTT.com, https://ifttt.com/recipes/182684-if-the-temperature-inside-drops-below-degrees-then-turn-off-a-c.

decrease CO concentration according to dynamic law (ODE $dCO/dt = -2$). So, the 195 ppm threshold of the purifier seems is correct that CO level will not go over 200 ppm. However, due to the existence of time delay of rule reaction, the CO level could exceed the threshold before the smart fan is activated. The HVAC example shares a similar story as well. Related efforts either simplify the problem down to discrete values [Liang et al. 2015; Liang et al. 2016], or they do not support arbitrary continuous behavior [Croft et al. 2015], which may cause false negatives in the verification. Second, all steps of system modeling, specification verification and violation fixing should be as transparent as possible to the user. Unlike typical CPS systems with domain experts [Clarke et al. 2008], relying on non-expert users is impractical due to the lack of background knowledge.

This paper realizes an end-to-end programming assistance to automate the modeling, checking, and fixing of HA-IoT systems. Specifically, this paper makes the following contributions:

Hybrid Automata Model Checking of Real Time HA-IoT System. As IoT devices are becoming customized commodity, it is important to help IoT users to ensure the confidence of the automation system they built. Motivated by IoT-specific characteristics, we take the first step to fill this gap with hybrid automata model checking. First, by using hybrid automata, it is possible for us to model and check the complex arbitrary continuous real time behavior of the analog system. This was previously unachievable by related efforts [Croft et al. 2015]. Second, in contrast to efforts which require user intervention in modeling and debugging [Liang et al. 2015], our work tries to automate all stages for non-expert IoT users.

Counterexample-guided Fix Suggestions. With each specification violation, the common practice is for the verification tool to output a counterexample, which is then analyzed by domain experts to fix the software problem. However, such an assumption does not hold in the case of non-expert IoT users. Instead, what should be provided is root cause analysis that pinpoints the IFTTT rule to fix. To this end, we present a method to parameterize the system, and synthesize the according parameters' values by quantifier elimination (QE) [Monniaux 2008] technique automatically.

System Implementation and Real Case Evaluation. We have been operating an IoT programing platform, MenShen, which implements our techniques. We check and fix a large real case including 46 devices and 65 rules in only 7.5 seconds. In MenShen, we also support and appreciate the interaction with users. If the users can select the specific rules they want to fix, or give the preferred range of rule parameters, MenShen can finish the aforementioned task in only 4 seconds with high user acceptance.

Structure of the Paper. The IFTTT-style IoT programming platform studied in this paper is presented in the next section. Section 2 also recaps the definition and verification technique of LHA, which works as the underlying decision procedure of this paper. After that, we present the architecture of our modeling, verification and fixing framework in Sect. 3. The detail of the automatic modeling technique and the verifiable schema behind this is introduced in Sect. 4. The verification and our new proposed quantifier elimination based fix suggestion is presented in Sect. 5. The system implementation and evaluation is reported in Sect. 6. Section 7 and 8 briefly discusses the limitation of this work and reviews the related work. Finally, the conclusion is stated in Sect. 9.

2. BACKGROUND

2.1. IFTTT-style Programming Paradigm for HA-IoT

Supporting interactions among digital real-time devices and analog environments, software system is at the center of home automation IoT (HA-IoT). This section dis-

cusses the current state of HA-IoT software systems, in terms of the programming paradigm and the unfilled gap.

Similar to wireless sensor networks, HA-IoT is a software system that reacts to changes in analog environments. For example, if the room temperature is below a threshold, the heater should be turned on. As such, the event-driven programming paradigm is widely used by real-world HA-IoT software systems, e.g., IFTTT [ift 2011], Apple HomeKit [ah 2016], and Google Brillo [gb 2016]. Being popularized by IFTTT, this paradigm is referred to as IFTTT-style programming. In IFTTT-style programming, an automation program consists of IFTTT rules, and these rules are executed in parallel. Individual rules follow the format of `if A then do B`, where `A` is a triggering sensor event and `B` is a triggered device command. In the example above, the former is the room temperature, and the latter is turning on the heater. By crawling the IFTTT website, we found that more than 34,000 HA-IoT rules have been created and shared by normal users, including: alerting when the room CO level is too high, shutting the heater when no one is home, etc. Depending on the number and types of connected devices deployed, a normal scale real case HA-IoT deployment typically has 10 to 30 IFTTT rules.

We argue that current HA-IoT software systems have the following unfilled gaps.

Lack of Automatic HA-IoT Confidence Verification. Since HA-IoT is a software system that controls IoT-enabled devices and appliances, any software bug (or unexpected behavior) can have ramification in the real world, even risk the user safety. For example, in our previous CO example, if the smart fan starts too late, the room CO level can go beyond 200 ppm and be harmful. Therefore, we argue an automatic confidence verification of certain system is crucial.

For formal modeling and verification to be practical, the HA-IoT programming tool suite must be able to automate as much as possible. While HA-IoT software systems for typical houses might not be as complicated as expert-built real-time control systems such as trains, the state space behind the IFTTT-style rules can quickly grow beyond non-expert users' comprehension. Furthermore, the time delay and different dynamic laws in the system is already too difficult for the normal end-users to understand. As we discuss in the next sections, techniques from hybrid automata can be the foundation of confidence verification solution, for HA-IoT solutions from the industry.

Lack of Debugging Feedback for Non-expert IoT Users. When a specification violation is identified, the common practice is for the verification tool to provide domain experts with a counterexample, or a sequence of system state transitions leading to the violation. Unfortunately, this feedback lacks sufficient information for non-expert users to comprehend the violation and pin-point the rules to fix. First, since a violation is caused by a sequence of rule execution, there is no clear indication which rule is at fault. And, the overhead of understanding the effect of each rule on the output can be high. Second, changing a rule in the execution sequence does not necessarily fix the problem, as doing so may also change what rules are triggered later in the sequence.

To fill this gap of debugging assistance, we propose to use quantifier elimination (QE) [Monniaux 2008] as the foundation to provide actionable feedback.

2.2. Modeling and Verification of Hybrid System

As we can see from the CO example, and the previous subsection, the behavior of HA-IoT system is tangling with both discrete logic control and continuous time behavior. Such a system is called a hybrid system. Linear hybrid automata (LHA) is a class of widely used formal language for modeling hybrid systems [Henzinger 1996]. The model checking [Clarke et al. 2001] problem for LHA is considerably difficult. The reachability checking problem is undecidable [Henzinger et al. 1998]. Classical techniques try

to compute the whole reachable state space of the LHA by the expensive polyhedral computation which is sensitive to the continuous variables and not guaranteed to terminate.

Recently, bounded model checking (BMC) [Biere et al. 2003; Audemard et al. 2005] has attracted lots of attention as an alternative to general model checking. The basic idea is looking for a counterexample in the given bound threshold instead of the complete state space. In this manner, the state space needed to search is controlled, and thus, can be efficiently checked.

Now, let's give a brief introduction to the definition of LHA [Henzinger 1996] and a state-of-the-art BMC reachability checking technique for LHA, the *path-oriented bounded reachability analysis* [Li et al. 2007; Bu and Li 2011].

Definition 2.1. An LHA H is a tuple $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$, where

- X is a finite set of real-valued variables; Σ is a finite set of event labels.
- V is a finite set of *locations*; v_I is the *initial location*.
- E is a *transition relation* whose elements are of the form $(v, \sigma, \phi, \psi, v')$, where $v, v' \in V$, $\sigma \in \Sigma$, ϕ is a set of *transition guards* of the form $a \leq \sum_{i=0}^{l} c_i x_i \leq b$, and ψ is a set of *reset actions* of the form $x := c$ where $x_i \in X$, $x \in X$, a, b, c and c_i are real numbers (a, b may be ∞).
- α is a labeling function which maps each location in $V - \{v_I\}$ to a *location invariant* which is a set of *variable constraints* of the form $a \leq \sum_{i=0}^{l} c_i x_i \leq b$ where $x_i \in X$, a, b and c_i are real numbers (a, b may be ∞).
- β is a labeling function which maps each location in $V - \{v_I\}$ to a set of *flow conditions* which are of the form $\dot{x} \in [a, b]$ where $x \in X$, and a, b are real numbers ($a \leq b$). For any location v, for any $x \in X$, there is one and only one flow condition $\dot{x} \in [a, b] \in \beta(v)$.

For a group of LHA $\{H_1, H_2, \ldots, H_n\}$, their composition, denoted as $N = H_1||H_2||\ldots||H_m$, is defined as a linear hybrid automaton from synchronizing all components with respect to the same event labels. Labels shared by several LHA models are called *Shared Labels*. The semantic of the shared label-guided synchronization is simple. Suppose several LHA models have a shared label, firing this shared label triggers the same transition in all models at the same time.

Definition 2.2. For an LHA $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$, a *reachability specification*, denoted as $\mathcal{R}(v, \varphi)$, consists of a location v in H and a set φ of variable constraints of the form $a \leq \sum_{i=0}^{l} c_i x_i \leq b$ where $x_i \in X$ for any i $(0 \leq i \leq l)$, a, b and c_i $(0 \leq i \leq l)$ are real numbers.

We use the sequences of locations to represent the evolution of an LHA from location to location. For an LHA $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$, a *path segment* is a sequence of locations of the form $\langle v_0 \rangle \xrightarrow[\sigma_0]{(\phi_0, \psi_0)} \langle v_1 \rangle \xrightarrow[\sigma_1]{(\phi_1, \psi_1)} \ldots \xrightarrow[\sigma_{n-1}]{(\phi_{n-1}, \psi_{n-1})} \langle v_n \rangle$, which satisfies $(v_i, \sigma_i, \phi_i, \psi_i, v_{i+1}) \in E$ for each i $(0 \leq i < n)$. A *path* in H is a path segment starting from the initial location v_I.

The question of whether a given path ρ in an LHA model H satisfies specification $\mathcal{R}(v, \varphi)$ has been well studied in [Li et al. 2007; Bu and Li 2011]. The basic idea is to describe the state space of ρ by encoding all the semantical elements, including transition guards, resets, location invariants, and flow conditions along this path into a formula together, denoted as Ψ. Then, whether ρ satisfies $\mathcal{R}(v, \varphi)$ can be translated

into the problem of the feasibility of Ψ, which can be solved by linear programming efficiently[3].

As we all know, the basic idea of bounded model checking (BMC) is to search for a counterexample in executions whose length is bounded by some integer k. Given an LHA, the number of candidate paths with length no longer than k is finite. Therefore, if we enumerate and check all the paths in the bound one by one, the BMC problem can be tackled. This is called as *path-oriented bounded analysis* [Bu and Li 2011; Xie et al. 2014] of LHA.

Now, we've reviewed the status of the latest HA-IoT industry, the definition of LHA, and also the path-oriented BMC analysis technique for LHA. From next section, we'll show how we can use such techniques in the HA-IoT industry.

3. FRAMEWORK OVERVIEW

As summarized in the above sections, the IFTTT-style HA-IoT system gives user high autonomy to build their own customized smart home automation system, with potential confidence risks though. As HA-IoT systems have extremely close relations with users' daily-life, it is crucial to give a mechanism which can help the users to increase the confidence of certain systems. In this paper, we propose an *automated framework for end-to-end programming assistance* to tackle this problem by performing the modeling, checking and fixing of such systems automatically. The framework shown in Fig.1 consists of the following parts:

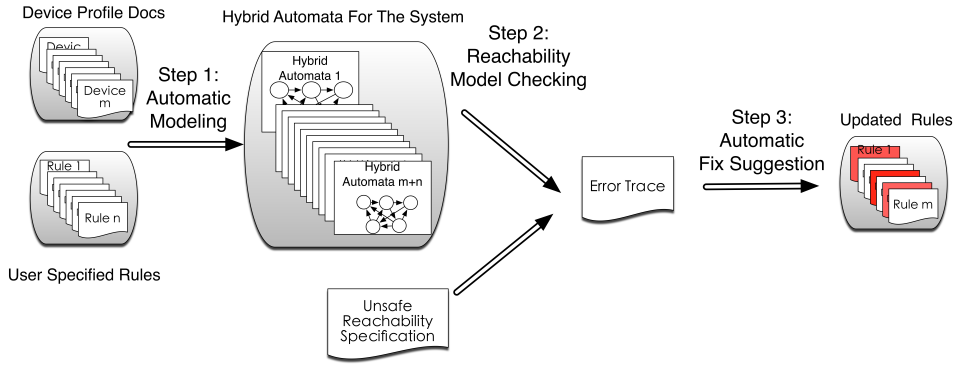

Fig. 1. The Architecture of The Framework

— Linear Hybrid Automata Automatic Modeling: The first phase of our framework is to generate the LHA models according to the devices and IFTTT rules in the system. It is unrealistic to ask a normal end-user to build the models of the system. Therefore, we design a specific schema where device manufacturers can present the necessary information of the device according to the format of such schema. Then, we can build the LHA model of the system from the device documentations and the IFTTT rules automatically.
— Reachability Analysis of LHA Model: The second phrase of our framework is to check the user specified unwanted reachability specification by the path-oriented BMC

[3]Due to the space limitation, we give a short review of the encoding of Ψ in the appendix of this paper. Readers are also refer to [Li et al. 2007; Bu and Li 2011] for the detail of such techniques.

checking procedure mentioned in Sect. 2. Clearly, if the unwanted target is not reachable, the system is good. Otherwise, we'll get an error trace, which describes the sequence of system events leading to a "bad" state.

— Counterexample-guided Fix Suggestion Synthesis: If the model fails the verification, the third phase is to help the user in debugging the counterexample. Again, as typical IoT users have insufficient knowledge in software testing and verification, providing guidance (e.g., fix suggestions) can be very helpful. To do so, we propose a method that first parametrizes the system, and subsequently solve the free parameters with quantifier elimination techniques.

4. VERIFIABLE SCHEMA AND AUTOMATIC LHA MODELING

In this section, we introduce the first part of our framework: Automatic LHA modeling. Clearly, it is impractical and not reasonable to ask the normal users to build the model for the devices and rules manually. Therefore, such task should be conducted automatically and systematically, if possible.

As we can see from the CO example, the aspects affecting the behavior of the HA-IoT system including the high level control logic, the time delay and dynamic laws dwelled in the system, the synchronization among devices and rules and so on. Therefore, Linear Hybrid Automata (LHA), which is the simplest model that can address all these aspects, is the most suitable modeling language of such HA-IoT system. Now, the question is how can we build the LHA model for such system automatically?

4.1. Verifiable Device Schema

Before building an LHA model, we need to get all the information needed about the device. Actually, IoT-enabled devices typically have a presence-advertising feature. It is common to see the manufacturer lists the working modes of the device, the public observable variables, the executable APIs and even simple dynamic laws in different places, e.g. advertisements, user manuals, device websites, piece by piece.

Clearly, manufacturers know all the information of the device. For the sake of automatic model generation, we argue each device should come with a profile documentation organized in a specific format that can express all the necessary information about the device. Actually, industry has started to propose such standard to present the information of a device in a organized way, for example Device Registry for AWS IoT (DR) [aws 2015]. Similar with the style of DR, which is readable and writable by manufacturers, we give the format of the verifiable device schema as follows:

— Device *Type* and *SN*, which indicate the type and the SN number of the device.
— A set of *System Variables*, which indicates the *environmental variables* affected by the device or the *internal data* kept by the device. In detail, if the value of a variable is observable by the user, we mark such variable as *public*.
— A set of device *Working Modes*, which represents the high level discrete working modes of the device. In detail, for each mode, there should include the *dynamic* information of how the system variables will be evolved in such mode. For example, in our CO example, when the smart fan is activated, the CO concentration in the room is going down by $dCO/dt = -2$.
— A set of *Transitions*, which indicates the internal mode changing logic of the device, like under which *triggering condition*, the device will change from mode A to mode B. There is also a special boolean flag *Signal*. If this flag is true, it means the execution of such transition is an *triggering condition event* that the environment can observe.
— Finally, a set of *API*s, which describes the kind of *triggered commands* that can be called by users and other devices. It has the same structure as *Transitions*. The only difference is that only API can appear in the right part of a IFTTT rule.

JSON [jso 2009] is a widely-used data format that can be parsed efficiently. We design a specific file format to express the above information in a JSON file. For example, Listing.1 and Listing.2 in Figure 2 give the JSON files for the devices in the CO example.

4.2. From Schema To LHA

Now, we present how to build the LHA model from the device schema automatically.

First, the LHA model for each device is modeled in the following way:

— The name, variables, locations and flow conditions of the LHA model can be generated based on the device schema directly.
— Each transition in the *Transitions* section becomes a transition in the LHA model.
  — If the *Signal* flag of the transition is true, then mark the label of the corresponding transition as *Signal_Transition.Name*. In this manner, other LHA models can communicate with this model by this shared label.
— The *API* section is treated differently. In detail:
  — If the *Signal* flag of the transition is false, then we treat it as a normal transition firstly. Then, as API could be called by other components/rules, whenever there is a new caller, we will add a new transition with the label *API.Name_Caller.Name*[4].
  — If the *Signal* flag is true, we add an intermediate location between the source and target location of certain API call. More specifically, we force the dwelling time of this intermediate location to be 0. Then, the previous API transitions will point to this intermediate location, and a new transition will be added from this intermediate location to the original target location with label *Signal_API.Name*. In this manner, no matter which caller executes this API, other components can receive the same signal. For example, we can see such locations and transitions in Fig.3.a and b.

For IFTTT rules, as each rule i has the same structure, the modeling can be done in a structural way.

— The structure of the IFTTT rule automaton is simple. There are two locations and transitions standing for waiting for the enabling of the triggering condition and ready to execute the triggered command.
— As the *triggered command* part of a rule can only be an API of a device, the label of the corresponding transition is *API.Name_Caller.Name*. In this case, it can communicate with the device automaton by this shared label.
— The *triggering condition* part could be the happening of an event/signal, or a triggering condition expression ϕ of an observable variable
  — If it is an signal, the label of the corresponding transition is *Signal_Transition.Name*.
  — If it is an expression, then we introduce a self loop transition in each location of the device automaton with the expression ϕ as the guard. The labels of the added device transition and in the rule model are both $Sensor\_Rule_i$.
— It is normal to see time delay between the enabling of the triggering condition and the execution of the corresponding API. Such delay can be marked as the invariants and guards in the model. For example, in Fig.3.c, we have invariant $t \leq 5$ on location $waiting$ and guard $t \geq 3$ on the transition $Close\_Rule_1$. This means the potential delay is $3 \leq t \leq 5$.

[4]We must distinguish different callers by transitions with different labels, because if different callers use the same label for one API, then they will be force to fire the transition at the same time according to the synchronization semantic of LHA

Listing 1. Smart Fan

```
{
  "Device":
  {
    "Type":"Smart Fan",
    "SN":"0001",
    "InternalVari":
    [
      {
        "Name":"CO_level",
        "Type":"double",
        "Default":"20",
        "public":"true"
      }
    ],
    "WorkingMode":
    [
      {
        "Name":"Closed",
        "Dynamic":
        [
          {
            "VariableName":"CO_level",
            "ChangeRate":"[-1,1]"
          }
        ],
        "Invariant":"true",
        "init":"true",
      },
      {
        "Name":"Working",
        "Dynamic":
        [
          {
            "VariableName":"CO_level",
            "ChangeRate":"-2"
          }
        ],
        "Invariant":"true",
        "init":"false",
      }
    ],
    "Transitions":
    [

    ],
    "API":[
      {
        "Name":"ACTIVATE",
        "StartMode":"Closed",
        "EndMode":"Working",
        "Trigger":"",
        "Assignments":[ ],
        "Signal":"true"
      },
      {
        "Name":"PAUSE",
        "StartMode":"Working",
        "EndMode":"Closed",
        "Trigger":"",
        "Assignments":[ ],
        "Signal":"true"
      }
    ]
  }
}
```

Listing 2. Alarm

```
{
  "Device":
  {
    "Type":"Alarm",
    "SN":"0002",
    "InternalVari":
    [

    ],
    "WorkingMode":
    [
      {
        "Name":"ON",
        "Dynamic":
        [
        ],
        "Invariant":"true",
        "init":"false",
      },
      {
        "Name":"OFF",
        "Dynamic":
        [
        ],
        "Invariant":"true",
        "init":"true",
      }
    ],
    "Transitions":
    [

    ],
    "API":[
      {
        "Name":"TURN_ON",
        "StartMode":"OFF",
        "EndMode":"ON",
        "Trigger":"",
        "Assignments":[ ],
        "Signal":"true"
      },
      {
        "Name":"TURN_OFF",
        "StartMode":"ON",
        "EndMode":"OFF",
        "Trigger":"",
        "Assignments":[ ],
        "Signal":"true"
      }
    ]
  }
}
```

Fig. 2. Json Docs For The CO Example

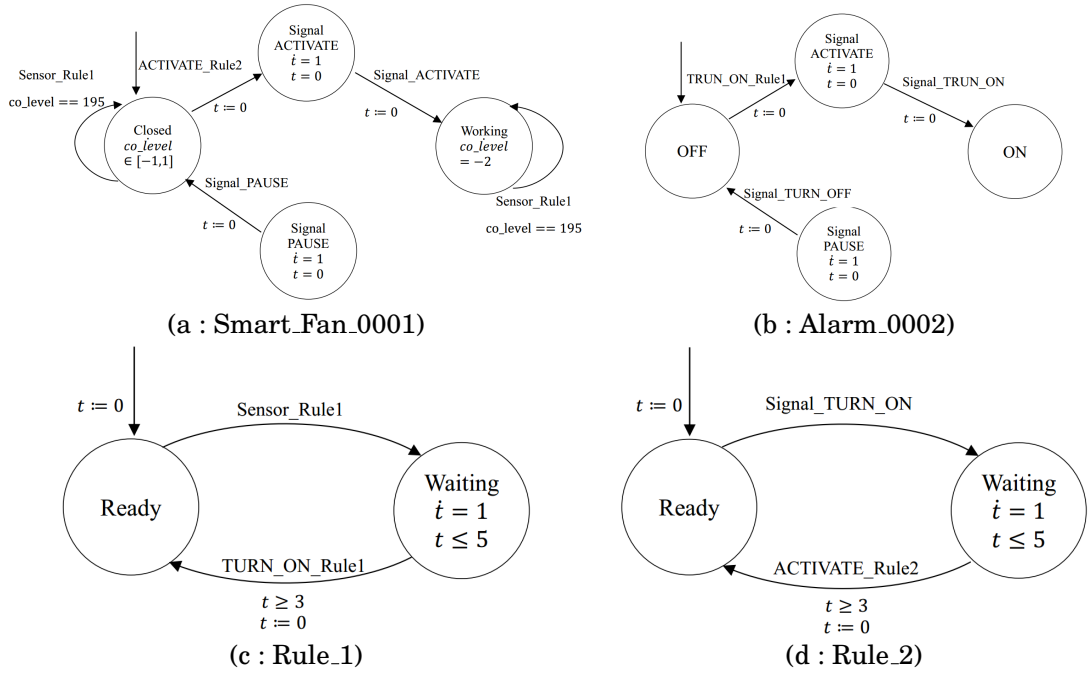

Fig. 3. LHA Models Generated For The CO Example.

Let's recall the IFTTT rule for the CO example given in section 1:

```
IF Smart_Fan.CO_reading == 195  THEN execute Alarm.TURN_ON command
IF Alarm.TURN_ON.Signal ==TRUE THEN execute Smart_Fan.ACTIVATE command
```

After processing the JSON schema, Fig.2, and the rules of the CO example, the corresponding LHA models generated according to the above rules are given in Fig.3.a-d respectively.

4.3. Feasibility of Verifiable Schema

About whether the modeling process can apply to a wide range of IoT devices, as both the industry and academia have been pushing hard in this direction. For example, the AllSeen alliance (which is backed up 50+ member companies such as Microsoft, Qualcomm, NetGear, HoneyWell, and LG) has a working group called Common Device Models. Similarly, Googles Weave protocol also mandates compatible IoT devices to provide device schemas. Furthermore, from the aspect of infrastructure, Amazons AWS offers IoT device registry services.

Building on this momentum in the industry, our contribution is to highlight device specifications that would be necessary for policy verification. In fact, most of these specifications are not difficult for IoT device manufacturers to provide. Furthermore, we discuss how these device specifications should be used, to achieve our goals.

5. SYSTEM CHECKING AND FIX SUGGESTION

The previous section presents a method to construct LHA models for a given set of HA-IoT devices and IFTTT-style automation rules. Now, we discuss approaches to efficiently check whether these models conform to specifications, and systematically synthesize solutions to resolve identified violations.

5.1. Specification Authoring and Specification-related Reachability Checking

Besides of the system model, the HA-IoT programming tool suite must allow IoT users to author confidence/reachability specifications. We note that specification should be easily readable/writeable by the non-expert users. To this end, we defines the specification format as a conjunction of conditions that *shall not happen*. This specification format is intuitive to non-expert IoT users, as it is similar to the IFTTT-style programming. In our CO example, if users do not want the room CO concentration to be higher than 200, they can write `SmartFan.CO` $\geq$ `200`.

After we get specifications from users, we can check whether the system of LHA models can never reach given undesirable state. One option is to conduct the BMC checking by directly using off-the-shelf checkers. However, this option can have a significant overhead, because these checkers always explore the entire state space of devices and rules, regardless of whether there are meaningful interactions among devices. At the same time, we note that the performance of state reachability checking can degrade quickly, as the number of components increases. Therefore, we propose to only consider the subset of models that are related with specifications, to shrink the state space for the underlying checker. This approach is formally presented next.

Definition 5.1. Given a composed LHA network $N = H_1||H_2||\dots||H_m$, and a reachability specification $\mathcal{R}(v, \varphi)$, if v is a location of H_i, φ consists of variables from H_j, $(1 \leq i, j \leq m)$, we say H_i and H_j are $\mathcal{R}$ *related*.

Definition 5.2. If two LHA models have a shared label, we say these two models are *related*. Given three LHA models, A,B and C, if A is related with B, B is related with C, then A is related with C. Given a composed LHA network $N = H_1||H_2||\dots||H_m$, we call the sets of all the LHA models related with H_i the *related closure* of H_i $(1 \leq i \leq m)$.

Definition 5.3. Given a composed LHA network $N = H_1||H_2||\dots||H_m$, and a reachability specification $\mathcal{R}(v, \varphi)$, if v is a location of H_i, φ consists of variables from H_j, $(1 \leq i, j \leq m)$, we say H_i and H_j are $\mathcal{R}$ *related*. Then, the set of LHA models consists of the related closure of H_i and the related closure of H_j is the $\mathcal{R}$ *related closure*.

Technically, given a reachability specification $\mathcal{R}(v, \varphi)$, we first compute the $\mathcal{R}$ *related closure* subset of models. Then, we feed it to the underlying checker to do the checking. In this manner, since the size of the system under checking is reduced, checking can be done with a smaller overhead.

5.2. Counterexample-guided Fix Suggestion

The output of BMC checking indicates either the set of models passes or fails the verification. If models fail the checking, it means there exists a sequence of transitions that can reach an undesirable state. In another word, bad things could happen. For IoT users, this potentially undesirable scenario should be resolved before the automation rule set is deployed.

Again, it is impractical to count on a normal end-user to fix the system based on his/her understanding of the counterexample trace. Even for a domain expert, debugging and fixing are not trivial. Meanwhile, as our framework is user-facing, there will not be an expert who can help the user to analyze and fix violations. Therefore, such tasks should be automated.

To resolve a specification violation, the first thing is to identify the problematic automation rule(s). Different from debugging for general CPS software, IoT users can realistically change only the automation rules, rather than changing installed IoT devices or specifications. Specifically, we can only adjust the triggering condition value of IFTTT rules.

Algorithm 1 Counterexample-guided Fix Suggestion

1: **procedure** CE–ANALYSIS (Counterexample Path ρ, Specification $\mathcal{R}(v, \varphi)$, Rule Set RS)
2: Encoding the reachability of ρ according to $\mathcal{R}(v, \varphi)$ as Formula Ψ
3: Denote the constraints related with all the rules in RS as Θ and the other rules in Ψ as Φ
4: Therefore, $\Psi = (\bigwedge_{i=1}^{n} \phi_i) \wedge (\bigwedge_{i=1}^{m} \theta_i)$, where $\phi_i \in \Phi$, and $\theta_i \in \Theta$
5: **for** each $\theta_i, (Device_i.variable_j == concrete\_value_k), \in \Theta$ **do**
6: Parametrize $concrete\_value_k$ to a free parameter $para_k$
7: Generate new constraint $\theta' = (Device_i.variable_j == para_k)$
8: **end for**
9: Generate formula $\Theta' = \bigwedge_{i=1}^{m} \theta'_i$, and $\Psi' = (\bigwedge_{i=1}^{n} \phi_i) \wedge \Theta'$
10: Take the negation of all the subformulas ψ_i in Ψ', get new formula $\Psi'' = \bigvee \neg\psi_i$
11: Denote all the variables in Ψ as $Vari$
12: Use QE to check: Whether $\exists para_k$, such that $\forall x_i \in Vari$, Ψ'' is feasible.
13: QE returns the value range for each $para_k$, which is the suggestion of the fix
14: **end procedure**

To systematically perform this task, we propose to parametrize IFTTT rules, and then solve for solutions to the parametrized system. Each of these solutions would represent one valid configuration, which can be presented to the IoT user.

In our CO example, suppose the reachability specification asks whether the CO concentration in the room can ever exceed 200. The checker finds a counterexample: as the smart fan detects the CO level reaches 195, rule 1 is executed. However, as there is delay between the satisfaction of the triggering condition and the execution of the triggered command, the CO concentration can reach 200 before the amart fan is activated. The original rule says `IF Smart_Fan.CO == 195 THEN Execute Alarm.TURN_ON`. We parametrize the rule to `IF Smart_Fan.CO == A THEN Execute Alarm.TURN_ON`. Then, we need to solve for values of A that can invalidate the specification.

Instead of computing the potential range of A directly, we propose a *counterexample-guided approach*. Our basic idea is to find values of A to dismiss the found counterexample path ρ. The algorithm is shown in Algorithm.1. As introduced in Sect.2, given a path in the model, whether the path satisfies the specification is encoded to the feasibility of a formula Ψ. Then, we parametrize the threshold of the triggering conditions in the rules to free parameters $para_k$, and we modify Ψ to Ψ' accordingly (line 5-9).

We can reformulate the problem as the following: can we find a valuation for these parameters to make Ψ' infeasible? If the answer is yes, then the located counterexample is dismissed. We take the negation of all the subformulas in Ψ', make a disjunction of them, and get new formula Ψ''. Now, the question become whether we can find $para_k$ to make Ψ'' feasible (line 10).

As all constraints in Ψ are linear, we can use quantifier elimination (QE) [Monniaux 2008] to transform this problem to an *equivalent* quantifier free numerical formula about $para_k$. This formula gives the value range for each $para_k$ that can make Ψ' infeasible, in another word, dismiss the found counterexample (line 11-13). Clearly, we can simply select a value in the range as a fix suggestion and ask the checker to check the system again. As the number of potential paths in the given bound is finite, this procedure is guaranteed to terminate.

Continuing the CO example, we first parametrize the condition `Smart_Fan.CO == 195` to `Smart_Fan.CO == A`. Then, we conduct the negation and QE procedures, as presented above. The resulted formula for A from QE solver is $0 \leq A \leq 190$, and the

Satisfiability Modulo Theories (SMT) solver selects a value from this range (e.g., 165). We use it as a potential fix, and check the set of models again. The system should pass the verification this time, and it subsequently presents the new value as a fix suggestion to the user.

5.3. Handling of Conditions of Inequalities

In the last subsection, the conditions of the triggers are all presented as equalities. The problem with inequality constraints is a little bit complex but still can be handled in a similar way.

According to the "lazy" semantic of LHA, when a transition guard is an inequality, the transition can be fired in any time spot which satisfies the inequality guard. In another word, the time spot that the transition is fired is not required to be the exact time spot that the guard is satisfied. Take the CO level for example, the transition guard `Smart_Fan.CO` $\geq$ `195` can be fired when CO level $\geq$ 1000, this still satisfies the semantic of the model.

As result, even we modify the condition to `Smart_Fan.CO` $\geq$ `165` as we did in the equality case, the model checker can still find a behavior which fires the trigger too late, when CO level is too high, say 1000. In another word, if the triggering condition is a half interval, the limitation of LHA semantic makes it difficult to control the timing that the transition will be fired.

Therefore, when our method needs to fix conditions with inequality of half-interval, it changes it to a parametric interval first. Still use the CO example, if the original condition is `Smart_Fan.CO` $\geq$ `165`, the parametrized condition is `b`$\geq$ `Smart_Fan.CO` $\geq$ `a`, where a and b are free parameters. Then, the line 12 of Algorithm.1 is changed to "Use QE to check: Whether $\exists a$, $\exists b$, such that $\forall x_i \in Vari$, Ψ'' is feasible". Then the following procedure is the same with equality.

In the CO example, the QE result we get is $300 \geq a \geq 0$, $190 \geq b \geq 0$, and $b \geq a$. The SMT solver selects value for a and b from the corresponding range respectively (e.g., a=75, b=180). So, we modify the condition to `180` $\geq$ `Smart_Fan.CO` $\geq$ `75`. We use it as a potential fix, and the system passes the verification then.

6. SYSTEM IMPLEMENTATION AND EVALUATION

This section is organized by the following major results. First, the technique proposed and discussed in this paper is implemented in a tool MenShen. Second, our optimization techniques allow MenShen to gracefully scale with the LHA size. Empirical results suggest that, for a deployment up to 46 devices and 65 rules, MenShen can finish within 10 seconds (i.e., the typical human attention span [Nielsen Norman Group 1993]). Third, user study confirms that most of the users cannot find the bug and fix the system. Meanwhile, the user study also suggests that more than 66.7% of fix suggestions are accepted, without further user intervention. The implementation of MenShen and all experimental data are available online [men 2016].

6.1. System Implementation Overview

Our current system implementation, MenShen[5], supports functionalities discussed in previous sections: (1) automated LHA model generation from device schemas, (2) template-based GUI for authoring IFTTT-style rules and specifications, (3) automated system reachability checking. and (4) violation fix suggestions.

MenShen is implemented in C#. Some system components are based on third-party libraries: BACH [bac 2006; Bu et al. 2008] for the LHA checker, Redlog [red 2006] for

[5]MenShen stands for the door god in Chinese.

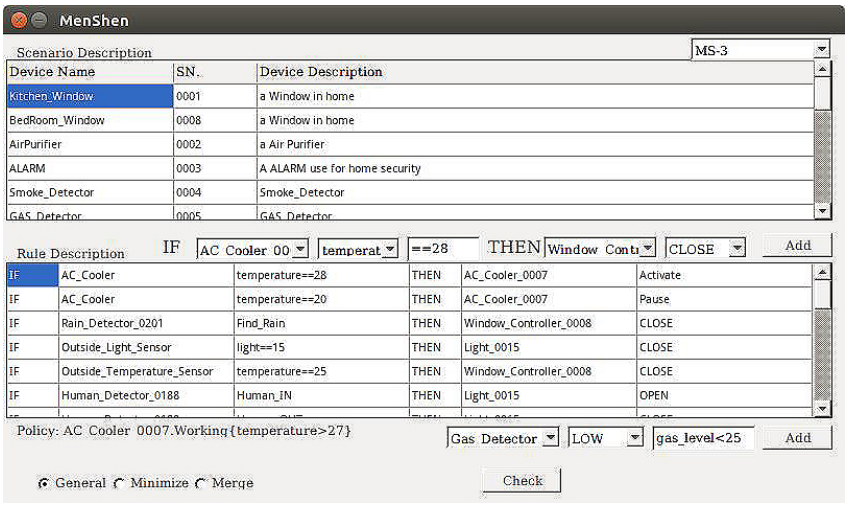

Fig. 4. Main GUI of MenShen

the QE solver, Z3 [de Moura and Bjørner 2008] for the SMT solver, and Json.Net [jso 2009] for parsing the device schemas.

Here we give the GUIs of the system to demo the functionalities of MenShen. The main GUI is shown in Fig.4, we can see that user can specify rules and the specifications by drop-down list-style templates. MenShen reads the information of devices from their docs directly. Then, users can select the name of the device, the variables that are observable, the APIs allowed to call to composite a rule/specification directly.

We can also find three options for the user to select before they click the check button in the bottom of Fig.4. The options including:

— General: No optimization technique is applied.
— Minimize: Perform the checking on the property related closure as described in Sect. 5.1.
— Merge: Link and analyze the rules with the same triggering condition as together. This prevents MenShen from assigning different thresholds while generating fix suggestions.

If MenShen find a violation of the specification, the fixing procedure could be activated. We grant users the option to mark rules that should never be changed. They can also provide the preferred range for individual variables. Then MenShen will look for solution in the user specified range. When multiple fix suggestions are possible, MenShen prioritizes the suggestions based on how similar they are to the original rules. Minimizing this difference can improve the user acceptance of fix suggestions. The related GUI is shown in Fig. 5.

After the fix suggestion is synthesized, MenShen will conduct a new round of confirmation checking. If the new system passed the confirmation checking, MenShen pushes the fix suggestion to the user, as we can see in Fig.6. The changed rules are marked by red color. Last but not least, if users are not satisfied with the fix suggestion, they are free to modify the rule and start the procedure again.

6.2. Real-world Evaluation Data Sets

Our nine data sets contain automation rule sets deployed in the real world. They are from three sources: (1) four small-scale systems (labeled as SC-1, SC-2, SC-3, SC-4) are

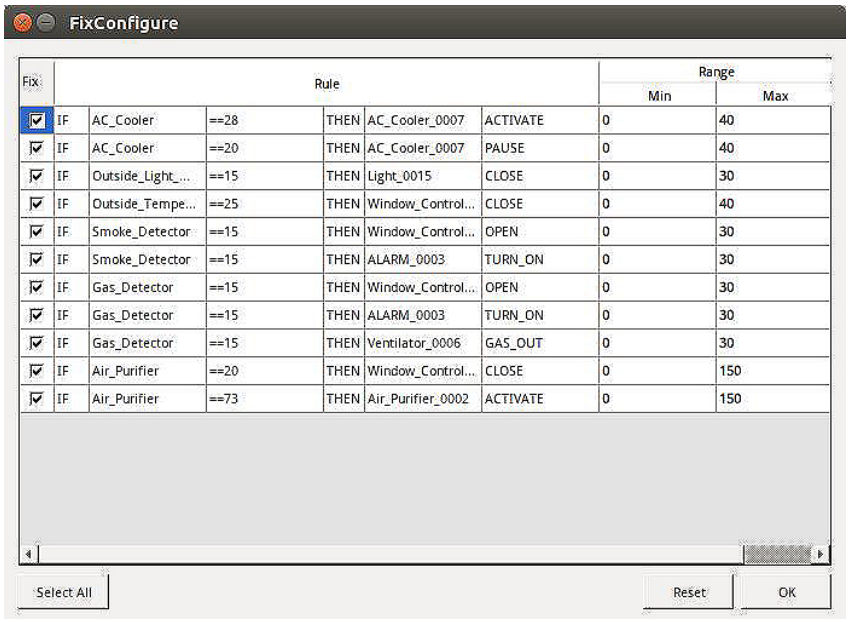

Fig. 5. GUI For Fix Configuration

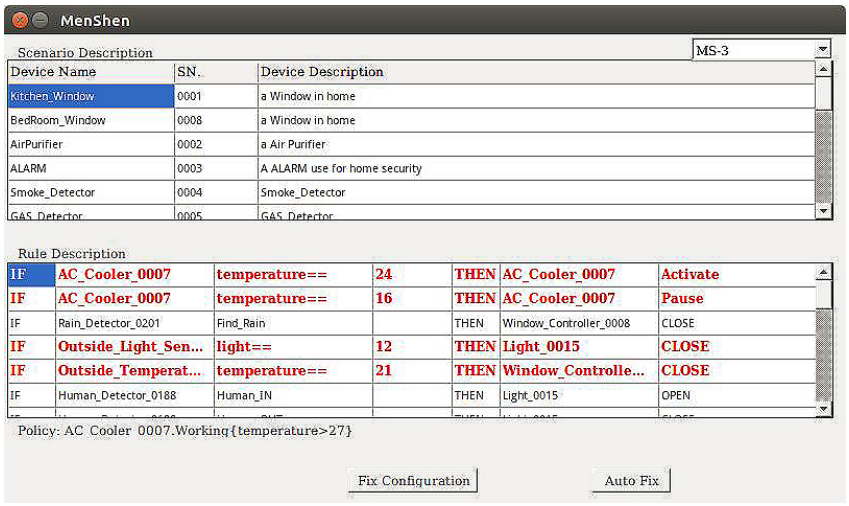

Fig. 6. GUI For Fix Suggestion

based on rules shared by normal IFTTT.com users [ift 2011]; (2) four large real-world HA-IoT systems are from office deployments (labeled as MS-1, MS-2, MS-3, MS-4); (3) one is used by a related effort [isy 2007][Croft et al. 2015] (labeled as ISY).

SC-1, SC-2, SC-3, and SC-4 have 2-3 devices and rules. Each of MS-1, MS-2, MS-3 and MS-4 has tens of rules and devices similar to typical home automation systems. The ISY data set has 46 devices and 65 rules. In total, there are 26 different types of devices including gas meters, HVAC, lights, air purifiers, GPS, water heater, etc.

Table I. System properties that data set owners expect their automation rule sets to satisfy.

System	Policy
SC-1	The hot water is ready when the user is back to home.
SC-2	The temperature of water in the bathtub should not drop down to 40 degree when the user is back to home.
SC-3	The level of CO in the room should never be dangerous.
SC-4	The home security should be closed when the garage door is opened.
MS-1	The level of smoke in the room should never be too high.
MS-2	The level of gas should never be dangerous.
MS-3	The temperature in the room should stay below 27.
MS-4	The level of PM2.5 in the room should not be harmful.
ISY	The light in the bedroom should be closed in 8:00pm.

Table II. Results of Checking and Fixing Real-case HA IoT Systems by MenShen. (#Devices and #Rules denote the number of devices and rules in the data set, respectively. #LHA denotes the number of generated LHA models. Check denotes the time spent in checking the problem. Fix denotes the time spent in fixing. The default bound we set for all the problem is 10 for all the automata.)

			Original System				System Minimization				Related Rules Merging			
System	#Devices	#Rules	#LHA	Model(s)	Check (s)	Fix (s)	#LHA	Model(s)	Check (s)	Fix (s)	#LHA	Model(s)	Check (s)	Fix (s)
SC-1	3	3	6	0.011	0.26	0.98	6	0.011	0.26	0.98	6	0.012	0.26	0.98
SC-2	3	3	6	0.011	0.26	1.25	6	0.010	0.26	1.25	6	0.011	0.26	1.25
SC-3	2	2	4	0.011	0.12	0.66	4	0.011	0.12	0.66	4	0.013	0.12	0.66
SC-4	3	2	5	0.010	0.22	0.92	5	0.013	0.22	0.92	5	0.013	0.22	0.92
MS-1	12	15	27	0.013	1.89	51.17	20	0.012	0.88	3.62	20	0.012	0.92	3.32
MS-2	12	15	27	0.012	1.79	365.58	20	0.013	1.23	8.62	20	0.015	1.02	7.88
MS-3	18	20	38	0.012	3.77	11.19	3	0.017	0.23	0.97	3	0.013	0.23	0.95
MS-4	18	19	37	0.013	3.56	10.5	3	0.012	0.23	0.98	3	0.013	0.23	0.95
ISY	46	65	111	0.014	9.25	1209.4	25	0.024	0.97	7.51	25	0.016	0.52	3.98

Table I lists the most important system property that data set owners expect their automation rule sets to comply.

6.3. System Scalability

MenShen aims to minimize the user burden in realizing high-confidence real time HA-IoT systems. Given that formal checking techniques are mature enough to accurately identify policy violations, this section discusses the system scalability in IoT scenarios. Specifically, we show that optimization techniques allow MenShen to exhibit a processing latency less than the typical 10-sec user attention span [Nielsen Norman Group 1993].

Experiments were conducted by checking whether individual data sets satisfy their expected system property listed in Table I. We used a ThinkCenter workstation, with Intel Core 2 Quad CPU Q9500 @ 2.83GHz $\times$ 4, 4GB RAM and Ubuntu 14.04 64-bit. The implementation of MenShen.

Table II shows the empirical results under three different MenShen settings: "Original System" refers to running MenShen without additional constraints; "System Minimization" refers to running the specification verification with only related models; "Related Rules Merging" refers to manually marking rule variables that should be the same (c.f. §6.1). As we discuss next, the system size (i.e., the number of LHA states) largely determines the system latency, and we also evaluated the effectiveness of two optimization techniques.

If the size of the system increases significantly, QE can be the performance bottleneck. Specifically, for the 4 small cases (SC-1, SC-2, SC-3, and SC-4), MenShen can complete both the checking and fix suggestions in less than 1 second. However, for the ISY data set, which is 20 times larger than the SC series cases, the latency increases quickly to 1,209 seconds.

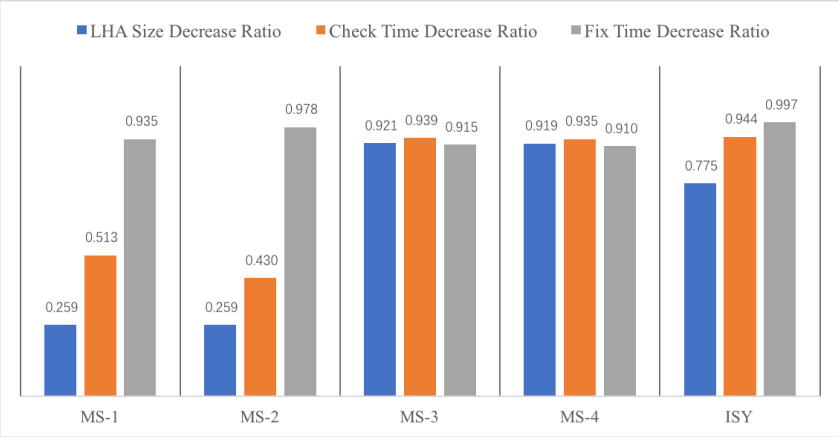

Fig. 7. Optimization Evalution: Related Rules Merging VS No Optimization

Table III. User Study on MS-4 Scenario from CS-Majored Students and Researchers.(Average Time denotes the average time spent by the participants in analyzing the specific problem. MenShen Time denotes the time spent by MenShen in the same problem.)

Problem	Total Partici.	Average Total Time(s)	Average Check(s)	Average Fix(s)	Able to Find Conflicts	Able to Fix	MenShen Check(s)	MenShen Fix(s)	User Acceptance
Q1	45	453	444	82	7/45	2/45	3.56	10.5	39/45
Q2	45	98	90	63	7/45	2/45	3.82	17.77	37/45
Q3	45	75	63	57	11/45	2/45	3.14	9.72	45/45

As discussed next, optimization techniques can reduce the system latency for large cases. Table II shows two such optimizations: System Minimization and Related Rules Merging.

First, when the system size is large, especially if not all the devices are connected with each other, the System Minimization technique exhibits a significant improvement space. Specifically, the number of automata in MS-3 is reduced from 38 to 3, and the number of automata in ISY case is reduced from 111 to 25. Since the entire state space is reduced significantly, the performance of MenShen improves substantially in all 5 large data sets. And, the time for ISY is reduced from more than 1,209 seconds down to only 7.5 seconds. However, we note that, since SC-1, SC-2, SC-3, and SC-4 are small data sets, the systems are very compact. Therefore, the gain from optimization techniques is negligible.

Second, we look at the gain from the Related Rules Merging technique. When the number of rules is large, it is not rare to have different rules sharing the same trigger conditions. In this case, while the number of automata under check stays the same, the structure for the related models can be simplified, to reduce the number of parameters to solve. As this optimization contains system minimization, we report the decrease ratio of "Related Rules Merging" versus no optimization on the 5 large problems about LHA size, time for checking and time for fix respectively in Figure.7. We can see the optimization methods work very well that up to 99.7% of time can be saved on large systems like ISY.

6.4. User Study

To understand the usefulness of MenShen's feedback to IoT users, we conducted a set of user studies with our real-world automation rule sets. Specifically, we took the MS-

Table IV. User Study on MS-4 Scenario from Non-CS-Majored Participants.

Problem	Total Partici.	Average Total Time(s)	Average Check(s)	Average Fix(s)	Able to Find Conflicts	Able to Fix	MenShen Check(s)	MenShen Fix(s)	User Acceptance
Q1	45	326	443	61	14/45	5/45	3.56	10.5	30/45
Q2	45	85	70	26	6/45	2/45	3.82	17.77	33/45
Q3	45	48	47	32	13/45	10/45	3.14	9.72	31/45

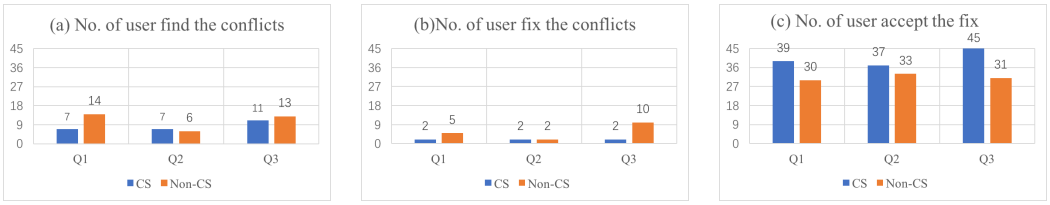

Fig. 8. Data of CS Major Participants VS Non-CS Major Participants.

4 data set, which represents a room with 20 IoT-enabled devices and 18 automation rules. And, we added two more system properties to check, to the one in Table II.

We have two group of volunteers. Each group has 45 participants. The study participants in the first group include researchers and interns from Microsoft Research Asia, and PH.D. and Master Students in software engineering discipline at Nanjing University. The participants in the second group include Non-CS major college students, high school students, and also some housewives.

We asked the participants to decide whether the connected IoT system can violate any of the 3 given specifications, and then we asked participants to attempt to fix these violations manually. Table III summarizes the user study results of the CS-Major users, while the results of Non-CS-Major users are presented in Table IV.

For comparison, these tables also include the performance of MenShen (without any optimization enabled). There are several observations to support the effectiveness of MenShen. For example, Table III and IV suggests that the majority of participants cannot find any violation after spending 1 to 8 minutes, and only four participants, two from CS-Major Group, 2 from the Non-CS-Major group, were able to identify and fix all the problems successfully. We can see that, for the majority of the participants, even for users with background in computer science, successfully realizing high-confidence HA-IoT systems is still a difficult task.

We've also organize and present the user study data of CS-major user and Non-CS-Major user in Fig.8. Interestingly, the percentage of user which can find and fix the system from Non-CS-Major is higher than CS-Major participants in many cases as shown in Fig.8.a and b. This supports our observation that, while the popular IFTTT-style programming paradigm simplifies authoring, it does not simplify the task of checking and fixing specification violations. For normal users of HA-IoT, even CS background education can not alleviate this problem as well.

Delving into Table III and IV, we discuss the user acceptance rate to MenShen feedback. Specifically, this metric is quantified by presenting MenShen's fix suggestions to the participants. Table III and IV show that, after we explained to the user the reason the system failed and fix the related rule, the user acceptance of the fix suggestions made by MenShen is satisfiable in the range from 66.7%(30/45) to 100% (45/45). One of the main reasons that some participants are not satisfied with the fix suggestion is that they have difficulty in understanding how the original parameter may cause error and why the changed version is correct. Therefore, we can see from Fig.8.c that the user acceptance rate from CS-Major group is higher than the Non-CS-Major group

in general. This brings an interesting topic about how to present the failure to users vividly in the future.

Besides of the above findings, one lesson learned is that, while several scenarios in a space can be programmed by a set of automation rules, IoT users tend to focus on manually verifying one scenario at a time. While this approach reduces the manual burden, it ignores interactions among scenarios. For example, turning on the HVAC can cause the air ventilation system to stop intaking outside air in the summer, which can have a undesirable consequence depending on indoor CO concentration. This observation brings up the value of having programming assistance from MenShen.

7. DISCUSSION

In this work, we demonstrate the feasibility of using linear hybrid automata (LHA) for HA-IoT systems. Not only does LHA simplify the presentation of device communication and the dynamic behavior of analog environments, it also efficiently checks the complex behavior. We now describe system limitations that are out of scope for this paper.

First, we currently assume device models are static and do not change over a short period of time. If the modeled environment is highly dynamic, parametric models [Bu et al. 2011] may yield better results. Furthermore, we note that it can be costly to model continuous analog environments that are under the influence of multiple IoT devices. For example, room temperature can be affected by outdoor temperature and indoor appliances. And, future work will focus on reducing this cost on the underlying system infrastructure. Second, the semantic of transition in LHA is not "Urgent" [Schupp et al. 2015]. Therefore, we may encounter situations where the trigger condition is enabled but the model does not fire such transition. Third, we currently do not consider human-in-the-loop, or user models that can change analog environments at any time. We leave this as the future work.

8. RELATED WORK

IoT Software System Checking and Monitoring. The high-confidence analysis of IoT systems has recently gained attentions in the community. SIFT [Liang et al. 2015] took the first step of demonstrating the potential of correctness checking of IoT systems, and it used the symbolic execution method to generate test cases to test the abstracted code of the IoT system. In contrast to MenShen, SIFT assumes IoT users have the necessary knowledge and background in running such procedure. Furthermore, SIFT does not consider the temporal behavior of devices, nor violation debugging.

Like MenShen, DeLorean [Croft et al. 2015] argues the importance of modeling the temporal behavior in checking HA-IoT systems. They proposed to build Timed Automata model for Home Automation control programs. However, they assumed a manual modeling procedure, which is not practical for non-expert IoT users. Furthermore, Timed Automata can only model time clock with uniform speed, rather than any continuous variable with arbitrary clocks. Therefore, MenShen can theoretically handle a wider spectrum of HA-IoT scenarios than DeLorean. Last but not least, they stop DeLorean after the checking is finished, but our work continues to synthesize fix suggestions.

DepSys [Munir and Stankovic 2014] presented a method to specify and check the dependency of devices in a home automation IoT system. However, they only focus on the potential conflicts among the devices, say, A and B control the same device. It does not address system-wide, especially time-related policy violations like MenShen.

Besides of the above efforts in correctness checking, there are also investigations in the area of invariant correctness monitoring [Gună et al. 2014; Herbert et al. 2007]. Generally, these works perform online monitoring of invariants about certain parame-

ters values to see whether certain values will break the invariant during system operation. Then, if an invariant violation is detected, predefined safety-related rules could be called in a similar way as IFTTT.

These works mainly focusing on the efficiency of runtime detecting certain invariant violation, say, catch the threshold in a timely manner. Be different, our work tries to make sure such violation will not happen. We perform an offline formal verification style checking to guarantee the correctness and we also help to fix the rules when the original system cannot meet the specification.

Parameter Fix Suggestion. The fix suggestion synthesis performed by MenShen is related to the classical parameter synthesis problem. This problem has been studied in many studies already. Studies [Henzinger and Wong-Toi 1995], [Frehse et al. 2008] are the most close works with MenShen as they are all able to deal with real time hybrid automata.

The problem of parameter synthesis for LHA was proposed in [Henzinger and Wong-Toi 1995]. However they need to compute the whole reachable set at first, which is very expensive. Thus, the system they can handle is rather limited.

Similar with this work, study [Frehse et al. 2008] also works on parameter synthesis for LHA. They propose a CEGAR framework to find the values for the parameters which can avoid the "bad" states in the complete state space. As MenShen is performing BMC rather than general MC, we are facing a much smaller state space. Therefore, we can use QE directly on the counterexample path to find potential parameter assignments.

Recently, study [Cimatti et al. 2013] proposed a method to perform optimal parameter synthesis for infinite state space system. They extended IC3 [Bradley 2011] framework to compute the precise region incrementally. This is an interesting work, we will try to adapt it into MenShen in the future work.

9. CONCLUSION

This paper presents MenShen, a novel framework of automated end-to-end programming assistance, to help non-expert IoT users in systematically realizing high-confidence real time HA-IoT systems. In contrast to related efforts that handle only high-level logic, MenShen can models and reasons about both real time behavior and analog environments. Furthermore, not only does MenShen check whether an automation rule set violates specifications, it also effectively suggests possible solutions to users.

As future work, we will investigate methods to model continuous aspects that are influenced by multiple devices and environmental factors. Personalized parameter generation is also an interesting topic which can help to increase user satisfaction. Furthermore, leveraging probabilistic model checking to generate user-friendly quantitative probabilistic reports of such HA-IoT systems is also worth of investigation.

APPENDIX

In this section, we give a review of the path-oriented reachability checking encoding presented in [Li et al. 2007; Bu and Li 2011]. This technique is the underlying decision procedure of MenShen for reachability checking.

For a path in an LHA H of the form $\langle v_0\rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \langle v_1\rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \langle v_n\rangle$, by assigning each location v_i with a time delay stamp δ_i we get a *timed sequence* of the form $\left\langle \begin{matrix} v_0 \\ \delta_0 \end{matrix} \right\rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \left\langle \begin{matrix} v_1 \\ \delta_1 \end{matrix} \right\rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \left\langle \begin{matrix} v_n \\ \delta_n \end{matrix} \right\rangle$ where δ_i $(0 < i \leq n)$ is a non-negative real number and $\delta_0 = 0$ as $v_0 = v_I$ is the initial location. This time sequence

represents a behavior of H such that the system starts from the initial location v_0, stays there for δ_0 time units, which is 0, then jumps to v_1 and stays at v_1 for δ_1 time units, and so on.

The behavior of an LHA can be described informally as follows. The automaton jumps from the initial location v_0 to v_1 to initialize all the variables. Then, as time progresses, the values of all variables change continuously according to the flow condition associated with the current location. At any time, the system can change its current location from v to v' provided that there is a transition $(v, \sigma, \phi, \psi, v')$ from v to v' whose all transition guards in ϕ are satisfied by the current value of the variables. With a location change by a transition $(v, \sigma, \phi, \psi, v')$, some variables are reset to the new value accordingly to the reset actions in ψ. Transitions are assumed to be instantaneous.

Let $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$ be an LHA. Given a timed sequence ω of the form $\left\langle \begin{matrix} v_0 \\ \delta_0 \end{matrix} \right\rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \left\langle \begin{matrix} v_1 \\ \delta_1 \end{matrix} \right\rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \left\langle \begin{matrix} v_n \\ \delta_n \end{matrix} \right\rangle$, let $\zeta_i(x)$ represents the value of x ($x \in X$) when the automaton has stayed at v_i for delay δ_i and $\lambda_i(x)$ represents the value of x at the time the automaton reaches v_i along with ω ($0 \le i \le n$). It follows that $\lambda_{i+1}(x) = \begin{cases} d & \text{if } x := d \in \psi_i \\ \zeta_i(x) & \text{otherwise} \end{cases} \quad (0 \le i < n)$.

Definition 9.1. For an LHA $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$, a timed sequence of the form $\left\langle \begin{matrix} v_0 \\ \delta_0 \end{matrix} \right\rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \left\langle \begin{matrix} v_1 \\ \delta_1 \end{matrix} \right\rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \left\langle \begin{matrix} v_n \\ \delta_n \end{matrix} \right\rangle$ represents a behavior of H if and only if the following condition is satisfied:

— $\langle v_0 \rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \langle v_1 \rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \langle v_n \rangle$ is a path;
— each variable $x \in X$ evolves according to its flow condition in each location v_i ($0 < i \le n$), i.e. $u_i\delta_i \le \zeta_i(x) - \lambda_i(x) \le u_i'\delta_i$ where $\dot{x} \in [u_i, u_i'] \in \beta(v_i)$;
— all the transition guards in ϕ_i ($1 \le i \le n-1$) are satisfied, i.e. for each transition guard $a \le \sum_{k=0}^{l} c_k x_k \le b$ in ϕ_i, $a \le \sum_{k=0}^{l} c_k \zeta_i(x_k) \le b$;
— the location invariant of each location v_i ($1 \le i \le n$) is satisfied, i.e. at the time the automaton reaches and leaves v_i, each constraint $a \le \sum_{k=0}^{l} c_k x_k \le b$ in $\alpha(v_i)$ ($1 \le i \le n$) is satisfied, i.e. $a \le \sum_{k=0}^{l} c_k \lambda_i(x_k) \le b$ and $a \le \sum_{k=0}^{l} c_k \zeta_i(x_k) \le b$

Definition 9.2. For an LHA $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$, if a timed sequence of the form $\left\langle \begin{matrix} v_0 \\ \delta_0 \end{matrix} \right\rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \left\langle \begin{matrix} v_1 \\ \delta_1 \end{matrix} \right\rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \left\langle \begin{matrix} v_n \\ \delta_n \end{matrix} \right\rangle$ is a behavior of H, we say path $\rho = \langle v_0 \rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \langle v_1 \rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \langle v_n \rangle$ is *feasible*, and location v_n is *reachable* along ρ.

Definition 9.3. Let $H = (X, \Sigma, V, v_I, E, \alpha, \beta)$ be an LHA, and $\mathcal{R}(v, \varphi)$ be a reachability specification. A behavior of H of the form $\left\langle \begin{matrix} v_0 \\ \delta_0 \end{matrix} \right\rangle \overset{(\phi_0,\psi_0)}{\underset{\sigma_0}{\longrightarrow}} \left\langle \begin{matrix} v_1 \\ \delta_1 \end{matrix} \right\rangle \overset{(\phi_1,\psi_1)}{\underset{\sigma_1}{\longrightarrow}} \cdots \overset{(\phi_{n-1},\psi_{n-1})}{\underset{\sigma_{n-1}}{\longrightarrow}} \left\langle \begin{matrix} v_n \\ \delta_n \end{matrix} \right\rangle$ *satisfies* $\mathcal{R}(v, \varphi)$ if and only if $v_n = v$ and each constraint in φ is satisfied when the automaton has stayed in v_n for delay δ_n, i.e. for each variable constraint $a \le \sum_{k=0}^{l} c_k x_k \le b$ in φ, $a \le \sum_{k=0}^{l} c_k \zeta_n(x_k) \le b$ where $\zeta_n(x_k)$ ($0 \le k \le l$) represents the value of x_k when the automaton has stayed at v_n for the delay δ_n. H *satisfies* $\mathcal{R}(v, \varphi)$ if and only if there is a behavior of H which satisfies $\mathcal{R}(v, \varphi)$.

According to Definition 9.2 and 9.3, the reachability of a given path in an LHA model can be encoded to the feasibility of a conjunction of a set of linear constraints, which can be solved by Linear Programming, SMT techniques efficiently.

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