Guardian of the HAN: Thwarting Mobile Attacks on Smart-Home Devices Using OS-level Situation Awareness

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Abstract—A new development of smart-home systems is to use mobile apps to control IoT devices across a Home Area Network (HAN). Those systems tend to rely on the Wi-Fi router to authenticate other devices; as verified in our study, IoT vendors tend to trust all devices connected to the HAN. This treatment exposes them to the attack from malicious apps, particularly those running on authorized phones, which the router does not have information to control, as confirmed in our measurement study. Mitigating this threat cannot solely rely on IoT manufacturers, which may need to change the hardware on the devices to support encryption, increasing the cost of the device, or software developers who we need to trust to implement security correctly.

In this work, we present a new technique to control the communication between the IoT devices and their apps in a unified, backward-compatible way. Our approach, called Hanguard, does not require any changes to the IoT devices themselves, the IoT apps or the OS of the participating phones. Hanguard achieves a fine-grained, per-app protection through bridging the OS-level situation awareness and the router-level per-flow control: each phone runs a non-system userspace Monitor app to identify the party that attempts to access the protected IoT device and inform the router through a control plane of its access decision; the router enforces the decision on the data plane after verifying whether the phone should be allowed to talk to the device. Hanguard uses a role-based access control (RBAC) schema which leverages type enforcement (TE) and multi-category security (MCS) primitives to define highly flexible access control rules. We implemented our design over both Android and iOS (>95% of mobile OS market share) and a popular router. Our study shows that Hanguard is both efficient and effective in practice.

I. INTRODUCTION

The pervasiveness of Internet of Things (IoT) devices has brought in a new wave of technological advances in home automation. According to Gartner [11], 6.4 billion IoT devices will be online in 2016, among which a significant portion are smart-home systems like smart thermostats [32], [15], fitness trackers, refrigerators, etc., and the number is expected to go above 20 billion by 2020. Examples of such devices include: the Belkin NetCam [5], a camera for streaming surveillance video to a mobile phone; the iBaby monitor [17], a device for remote babysitting; the Family Hub refrigerator [41], which enables online checking of the fridge’s contents. Increasingly, these devices are designed to communicate not only with their servers in the cloud but also with other IoT devices and the user’s phone over the Home Area Network (HAN), which is typically built around a Wi-Fi router. For example, Nest Protect Fire sensors [31] are capable of propagating an alarm across multiple sensors installed in different rooms of a house. For the convenience of management, such interconnected IoT equipment often relies on the secure connections of HAN (Wi-Fi authentication) for protection and trusts all the computing systems on the same network. This treatment, however, completely exposes the device to the attacks from compromised local systems, a threat becoming increasingly realistic.

Menace of local threats. Indeed, it has been reported that high-profile WiFi-enabled smart home devices, including the WeMo Switch and motion sensor [54], [87], [99], [112], [113], Belkin NetCam [6], baby monitoring devices [116], [115], [114] and smart light bulbs [80], are all vulnerable to a local attack: an adversary within the same HAN is shown to be able to control those devices or steal sensitive user information, e.g., live video streams [6], from them. Several studies further reveal that this is possible since such devices have poor—or no—authentication mechanisms [100], [20], [95], [106], [88], [82], [83], [38], [101], [38] and therefore easily fall prey to a local attacker.

Defending against such attacks becomes particularly challenging when the IoT devices are controlled by phones: once the same phone also carries malware (even when the app has nothing but the network privilege), protecting the device it controls becomes impossible at the network level, as the phone is completely legitimate to access the device though the malicious app running on it is not. Given the high smartphone penetration rates [103], the millions of available mobile applications on both official and third-party markets [35], and the ease of distribution of such applications 1, devices that can be reached through mobile apps can also become an easy target to adversaries. Unfortunately, such adversaries are not

1Android applications can be self-signed.
only realistic; they are on the rise [1], [24], [45]. Because of that they become the main subject of study of many other academic works [61], [124], [81], [122] while concerns are also raised on public communication channels [47], [2], [25]. In our research we verified that IoT vendors tend to trust the local network (Section III-B). This makes them vulnerable to a mobile adversary as we illustrate with attacks on real-world IoT devices, including the WeMo Switch, WeMo Motion, WeMo in.sight.AC1 and My N3rd. The demos of these attacks can be found on a private website [13].

Addressing the issue here cannot solely rely on device manufacturers: unfortunately business factors such as time to market and keeping the cost of the device low but also operational factors such as low power consumption, lead to the production of devices without encryption capabilities [104]. In such cases, response to threats can only be reactive and it would entail manufacturing a new version of the device which would still leave users with the old version susceptible to attacks. To make things worse, device manufacturers can be slow in responding [10], [105] to security and privacy threats. Router vendors have already identified this threat. New hubs and routers pushed onto the market are increasingly armed with various IoT protections (e.g. Microsoft Azure IoT hub [4], Google’s OnHub router [36]. Integrating protection and management capabilities in the router has significant benefits as the infrastructure is already in place in most households and it enables unified policy management. However, as mentioned above, security control at the router level cannot succeed without knowledge of the OS-level situation within an authorized mobile phone, particularly whether a request to a target device comes from its official app or an unauthorized party. Fundamentally, a practical solution to the problem needs to bridge the gap between the OS-level observation (apps making network connections on a phone) and the network-layer view (requests from the phone for accessing an IoT device), with minimum modifications on the HAN infrastructure and all the systems involved.

**Situation-aware device access protection.** A simple solution to the problem is just inferring the identity of the app communicating with an IoT device according to its traffic fingerprint. This approach, however, is unreliable and can be easily defeated by, for example, a repackaged app that closely mimics the authorized program’s communication patterns. Also, individual apps’ fingerprints need to be reliably generated, deployed and continuously updated, and further to be checked on the router against each communication flow it observes, which adds cost to both the router developer and the user. In this paper, we present a different approach, a new technique that achieves fine-grained, situation-aware access control of IoT devices over a home area network. Our approach, called Hanguard, distributes its protection logic across mobile phones and the Wi-Fi router for jointly constructing the full picture of an IoT access attempt during runtime, which is then utilized to control the access on the network layer. More specifically, on the phone side, the information about the app making network connections is collected and passed to the router; on the router side, security policies are enforced to ensure that only an authorized app can touch a set of functionalities the device provides. In this way, malware on network-authenticated phones can no longer endanger the operations of the IoT devices, even when the IoT devices are not equipped with proper authentication and encryption protection.

Hanguard is designed to directly work on the existing HAN infrastructure, without modifying mobile operating systems or IoT devices. To deploy the system, one only needs to install a Monitor app with non-system privileges on mobile phones and update the firmware of the Wi-Fi router with a security patch. A key technical challenge here is how to gather situation information (processes making network connections) on mobile phones, which is not given to a third-party userspace app on both Android and iOS. Although all these systems provide VPN support, the app using the service still cannot observe the process generating traffic and will significantly slow down the network communication of the whole system (Section IV-B). To address the issue, we leverage side channel information for lightweight discovery of runtime situation on Android and utilize the VPN to only mark out authorized apps’ traffic on iOS (Section IV-B). Such information is then delivered to the router through a separate control channel, which is synchronized with the traffic generated by the app (over a data channel) and used by the router to determine whether the communication should be allowed to proceed.

We implemented our design over both Android and iOS which cover more than 95% of the mobile OS marketshare [18], and a TP-Link WDR4300v1 Wi-Fi router. Our evaluation shows that Hanguard easily identified and blocked all unauthorized attempts to access IoT devices with negligible overhead in the common case. (Section V).

**Our contributions.** The contributions of the paper are summarized as follows:

- **New understanding.** We found that IoT vendors treat the HAN as a trusted environment. This treatment leaves the devices vulnerable to a new type of confused-deputy problem, when a malicious app utilizes an authorized phone to gain unauthorized access to IoT devices through the HAN. We further demonstrate the grave consequences of such attacks on four real IoT devices. Our findings highlight the need for proactive protection built within the HAN.

- **New access control mechanisms.** We have utilized type enforcement and multi-category security principles to design a new fine-grained access control mechanism for WiFi devices.

- **New system techniques.** Hanguard employs a new software-defined networking (SDN) approach applied on existing infrastructure of home area networks: it features a new controller system architecture distributed across HAN phones and the router. To the best of our knowledge we are the first to use phones as Monitors for local area SDN. Our design can have applications in enterprise settings, peer-to-peer networks and others.

- **Implementation and evaluation.** We implemented Hanguard
on both Android and iOS phones, and a commercial router, and evaluated it against attacks on real-world IoT devices and on various performance metrics. Our study demonstrates the practicality and efficacy of the new system.

**Roadmap.** The rest of the paper is organized as follows: Section II motivate the work and Section III presents our study on popular smart-home devices; Section IV presents Hanguard and Section V our evaluation; Section VI conducts a security analysis of our system and Section VII discusses Hanguard.; Section VIII reviews related prior research and Section IX concludes the paper.

### II. Motivation

**IoT on HAN.** Home automation systems today are increasingly connected to the Internet and to each other. Examples of such devices include smart cameras [5], [8], [3], [30], [14], various sensors [31], [54], [23], [7], [33], [39], smart door bells [40], [43] (with HD video, motion sensing and bidirectional audio capabilities), smart cooking appliances like Mr Coffee [26] (for remote control of coffee brewing), smart gardening products such as OpenSprinkler [37] (for remote management of irrigation) and more. These devices are typically connected to a HAN through its Wi-Fi router. To make this happen, one uses a smartphone to communicate with a temporary access point created by the IoT device to configure the device, entering login credentials for the device to establish a Wi-Fi connection with the router. Through the connection, the device can talk to its cloud service and receive commands from the service and the user’s phone. A conventional way to do that is to let the phone control the device through the cloud service, even when both the phone and the IoT devices are within the same HAN.

Although this treatment simplifies the IoT-control mechanism, restricting an authorized app to always communicate with the IoT device in the same way regardless of whether they are on the same network, it comes with availability and performance penalties. In fact this has already caused a lot of trouble: e.g., the Ring doorbell [68] is reported to take 30 seconds to deliver the notification to the user in some cases; Canary [63] and Scout alarm [22] was found to be unable to send out an alarm once the Internet is down. Also users of the Lutron bridge [9] and the Chamberlain garage opener [78] complained that they need the Internet to turn on the light and open the garage door. In response to such concerns, support for direct phone-device communication through the HAN becomes a requirement. For example Lightify claims that from version 1.0.3b11, its users will be able to control lights offline [21]. Another prominent example is Samsung’s Smarthings—a leading IoT hub: Smarthings reported their plans to support local computation, which enables its systems to work together even without Internet [34]; in fact apps and devices which previously existed in the cloud, are now moved to the local hub [46].

**Smart-home security.** The popularity of the smart-home devices also comes with new security risks. As mentioned earlier, several studies show that most IoT devices today are not adequately protected, leaving the door widely open to different kinds of attacks. A prominent example is Shodan [42], [95], [106], a search engine for IoT, which has discovered a lot of vulnerable webcams online (ports made open to the public and with only weak authentication protection), exposing private information such as video streams of a sleeping baby [85]. Moreover, a recent Mirai-based botnet, took advantage of smart-home devices weak authentication to launch a massive DDoS attack in the US [16]. In addition to such remote attacks, smart-home devices are also found to be subjected to local threats. It has been reported that through a laptop or a desktop running in the same network, one can gain unauthorized access to the Wemo Switch and Motion sensor [87], [99], [112], [113], the Belkin NetCam [6], the Philips Hue smart light bulbs [80], etc. Our research further shows that such attacks can be launched from a malicious app running on a smartphone and the problem becomes particularly serious when the phone is authorized to access the IoT device while the app is not (Section III-B).

Such mobile malware have been established as one of the most prevalent cyber-threats. On the one hand some reports show low mobile device infection rates by malicious applications in the US [93], but on the other hand these reports are somewhat variable [74]. Furthermore, there are increasingly more potentially harmful applications in other parts of the world e.g. in China. More importantly, the mere presence of mobile malware given the ease of their distribution (self-signed apps, third-party markets) and the rise of mobile malware [1], [24], [45], render it a security threat. Mobile malware became the main subject of study of many previous academic works which have already illustrated the prevalence and severity of this problem [61], [124], [81], [122].

**Need for proactive device-independent protection.** One way to mitigate the mobile adversary on home IoT devices is by fixing all the security vulnerabilities on the IoT devices. However, it is generally accepted that fixing the security issues within embedded devices is difficult [10], [105], [104]. Unlike traditional computers, whose security-critical vulnerabilities are often addressed through patching, no clear path is available for patching and upgrading IoT devices once they leave the manufacturer’s warehouse. The problem is caused by a lack of computing power on some devices or the patching infrastructure, or in some other cases, by the use of third-party hardware, software and other resources, which are hard to patch by the device manufacturers themselves. Consider for example, the case of the square dongle which is used for secure payments. Driven by time to market goals and low cost requirements, the vendor shipped the earlier version of the dongle with no hardware support for encryption [104]. To fix the problem, Square had to produce a new dongle device. Moreover, previous work [98] demonstrated that various Bluetooth medical devices also suffered from similar issues, lacking authentication and encryption. As a result of such practices, many faulty systems are still in use even after their problems have been reported, leaving them even more vulnerable since their weaknesses already become public knowledge. Lastly, many reports indicate
that these problems extend to IoT devices [20], [95], [106], [88], [82], [83], [38], [101], [38]. We believe that the answer to this challenge for smart home WiFi devices, is a network-level protection that utilizes distributed app-level awareness from existing user-managed devices. The system should be deployable on the existing HAN infrastructure; it should also enable access control management of smart-home devices and safeguard them and their users even when the devices themselves are vulnerable.

III. OPERATIONS AND EXISTING TRUST MODEL

We performed an analysis of devices’ operations, their HAN trust model and the implications stemming from a mobile adversary. Our findings informed Hanguard’s design decisions.

Methodology. One approach for our study would be to investigate the IoT devices’ firmware. That would entail—after identifying such devices—finding images of their firmware or, for each device, buying the device and extracting its firmware. Subsequently, each firmware needs to be analyzed, which is a non trivial task [69]. However, most of these devices are now controlled by mobile apps. Thus their control mechanisms can be examined by analyzing the apps instead of the firmware. Note that, our approach has multiple benefits over analyzing firmware: (1) we can easily acquire Android apps, (2) there is no monetary cost, (3) it is generally easier and faster to analyze mobile apps than an embedded device’s firmware.

The most straightforward way to find the Android apps of the IoT devices, is to search for them at Google Play using keywords such as “home automation” and “internet of things”, which, however, turned out to be less effective: through manual inspections of search outcomes, we found that many apps identified this way were not related to any IoT systems and in the meantime, popular IoT apps fell through cracks. Our solution is to crawl iotlist.co, a popular site for discovering IoT products. From the list, the crawler we ran collected the meta-data of 353 products, including “Title”, “Description”, “Product Url”, “Purchase Url” and others. Such data was further manually checked to identify a list of package names for the official apps of these devices. Searching Google Play using the list, our crawler downloaded the apps and their meta-data from the Play store. Out of the 353 products we found that 63% (223) of them have apps on Google Play, 2% (7) are iOS only and the rest are mostly unfinished products (listed on kickstarter.com and indiegogo.com) or are no longer available. This indicates that indeed most IoT devices today are controlled by smartphones. The APK files of these apps were decompiled (using apktool [49]) and their .smali files and manifest files were extracted. Further, each app’s machine code was converted to Java code using dex2jar [12] for manual analysis.

A. Operations of Smart-Home Devices

To better understand the operations of smart devices, we manually went through (1) the meta-data of the collected products, (2) their online documentations and websites, and (3) through their apps’ source code when available. Figure 1a illustrates our manual categorization of the IoT products based on their functionality. Note that the Wearables category (31%) embodies mostly fitness and location trackers, smartwatches and personal medical devices. We call such devices personal devices; these commonly use Bluetooth to connect to a smartphone app. Previous work has already studied the security of personal devices, they found problems with encryption and authentication and proposed solutions [98], [72]. From the figure, we can also see that most of the listed IoT devices (55%) are smart home automation/entertainment/security/hub systems, which are the focus of our study (see Appendix X for a complete categorization). We call these shared devices. Such devices could directly benefit from an access control scheme built within the HAN. Previous work on shared devices, was focused on a single IoT integration platform (hub) [75], [76].

In our research we wanted to identify the workflow of the WiFi-enabled smart-home devices irrespective of the existence or non existence of a proprietary integration platform (hub). We identified 2 high level phases of operation: the setup phase and the communication phase. During the setup phase, the system provides the user with the means of communicating the WiFi credentials to the smart device. Then the smart device uses the credentials to authenticate itself to the local network. Figure 1b illustrates the most common setup scenario among the WiFi devices. In Step 1, the smart device creates a micro access point and advertises its SSID. This is is usually initiated by the user pushing a specific sequence of buttons on the device. In Steps 2, 3 and 4, the user utilizes a smart phone app to directly connect to the device. The app searches for the advertised SSID and guides the user to select the device network. Once the smartphone connects to the micro-access point, the app asks the user to input the HAN WiFi credentials to the app (Step 5). Then the app transfers the credentials to the device (Step 6). In Step 7, 8, and 9, the device tears down the micro-access point and attempts to connect to the HAN WiFi network. The user is notified through the app regarding the result of the attempt (Step 10). Once the device is connected to the HAN the app asks the user to connect her phone to the HAN as well to interact with the device (Step 11). Other IoT vendors choose to complete the setup phase through a tethered mode: the user is expected to connect her smartphone with the device through a cable (e.g. audio jack, usb). The credentials are passed by the app using the tethered channel. Evidently the setup phase can be cumbersome to the users but is expected to happen mostly once per device. Some vendors do try to streamline this process. For example some devices use a no-network mode. In this case the user could input the WiFi credentials to the app and then show the smartphone screen to an optical sensor on the device. The device recognizes and parses the credentials. During the communication phase, the user can send com-
mands to the smart device through the app. This can happen through 2 main avenues as illustrated in Figure 1c. The app can (a) attempt to connect to the cloud service of the device. In this case the cloud service is responsible for authenticating the app and relaying the command to the appropriate IoT device. Alternatively (b) the app connects directly to the device through WiFi. Obviously the former requires constant Internet connection and comes with latency penalties. Thus vendors (e.g. Samsung Smarthings) are increasingly turning into using the cloud only for remote control and turning to WiFi for local control.

B. HAN Trust Model of Smart-Home Devices

In our research, we further investigated the trust model of WiFi smart-home devices. Prior research already demonstrated that the interaction between smartphone apps and the cloud is alarmingly unguarded [66], [119]. On the other hand, the local communication between the apps and the devices is not as well understood. In fact it is unclear whether app developers and IoT device manufacturers treat the local network and everybody connected to it as trusted entities and whether such treatments leave the devices susceptible to attacks from both local adversaries and remote adversaries that gain access to the HAN. Moreover, even though it has been reported that IoT devices come with serious problems [20], [95], [106], [88], [82], [83], [38], [101], [38], little has been done to understand the security risks stemming from malicious mobile apps. This is particularly important since, IoT devices are controlled by apps which send commands either through the cloud or the local network. Here, we aim to bridge these gaps in knowledge. Our findings build on to the existing evidence which collectively support the need for a unified security and management system built within the HAN to safeguard today’s smart-home devices.

To facilitate our manual analysis we further built a parsing tool which simply looks for the presence of password requests in the layout files of the apps. Android enables developers to create the layout of a screen statically using xml layout files. In such files, one can specify a hint to a text field using android:hint="my_hint". Developers can also explicitly associate a field with a password using android:password="true" for API level 3 and earlier, or android:inputType="textPassword" for later versions. Our tool looks in all xml files under the layout directories of an app under analysis for the presence of these definitions; where my_hint we used password and passphrase.

Our study aims to achieve the following goals: (a) Find out whether vendors and developers of WiFi smart home devices/apps erroneously treat the home area network as a trusted environment; (b) Find out how easy or hard it is for a mobile adversary to take advantage of unguarded local smart home devices in practice.

HAN Trust Model. We performed a statistical significance test focused on the following null hypothesis ($H_0$): HAN apps with only remote connections are equally likely to perform authentication compared to HAN apps with only local connections. To answer this question we separated our collected IoT apps into two groups. Apps with only remote connections and apps with only local WiFi connections. We used 55 unique Android applications with WiFi/Internet only connections to HAN IoT devices. A full list of the apps selected for HAN trust model analysis is provided in the Appendix X.

To separate the apps into the two groups, we manually went through (1) their online documentations and websites, (2) public forums, and (3) their Java Android code. We found that 22 (40%) do perform some internet socket connection with local discovered devices or fixed local IPs. 25 (45%) were found without local WiFi connections, 5 (9%) we could not determine, for 2(4%) decompilation failed, and 1 (2%) was by that time removed from Google Play. For each of the 2 sets (local; no local) we analyzed them further to discover whether they perform any authentication. For the ones that perform only remote connections we used our parsing tool that searches for password requests in the layout files of the apps. We found that out of 25 apps, 16 do request a password and 9 do not. Since, our tool could miss password requests that are not defined statically, we manually went through the 9 apps flagged as performing no authentication and found that actually a password was used in some respect in all 9 of them. In particular, 7 of them were web apps using libraries such as the cordova library that allows developing apps with web technologies (e.g. Javascript). The remaining two were constructing the user interface element responsible for the password field in code.

For the 22 apps with local WiFi connections we could not

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Note: if the connection is construed to be performed for the *setup* phase, we do not regard it as a local connection.
simply use the above tool since it would reveal little to no information on whether a password is used for a connection with the IoT device or the cloud. Thus we manually went through their code looking for network API calls responsible for local connections (e.g. creation of sockets connecting to local IPs, or UPnP discovery). We examined the calls to such APIs and found that 9 of the apps do not authenticate to the IoT device.

To determine whether apps with local connections are less likely to perform authentication one could perform a $\chi^2$-test of independence. A challenge we had was the small absolute number of relevant available apps derived from iotlist.co. Because of this, the $\chi^2$-test of independence might not derive statistically significant results. To overcome this we used the Fisher’s exact test [77]. This is a common approach to derive statistically significant results when the sample size is small. We leveraged a tool by Carlson et. al. [65] to perform such a test on the null hypothesis ($H_0$). A 2-sided $P$ value less than 0.05 was considered significant.

The test yielded a 2-sided P-value of 0.00036 < 0.05 and thus we can reject $H_0$. Therefore, we can now confidently say that HAN apps with local connections are less likely to get authenticated by smart-home devices. This validates an important intuition that IoT vendors consider the HAN to be a trusted environment. However, given the fact that phones are an integral part of such a network and that phones can carry self-signed apps from third-party markets, this treatment becomes detrimental to the security of HAN IoT devices. This result further highlights the need for an access control system that can be integrated in home area networks with minimal changes to the existing infrastructure, that is backward compatible, independent of vendor and developer practices and that allows the users the flexibility to manage and control who should communicate to which device.

**HAN mobile adversary.** The previous finding is particularly alarming. Next we attempt to illustrate how a weak mobile adversary can take advantage of this problematic trust model and compromise smart home devices. Towards this end, we cherry-picked four devices with local connections and authentication issues and attempted to perform real-world, practical attacks. The devices we picked are listed on Table I. Our targets include the WeMo Switch and WeMo Motion [54], the WeMo Insight.AC1 [53], and My N3rd [27]. The WeMo devices are examples of popular plug-and-play devices. Just on Android, the official app of the WeMo devices was downloaded 100,000–500,000 times. Note that all the WeMo devices are manufactured by a single vendor. By focusing on three WeMo devices we want to showcase how an erroneous trust model by a vendor can spread across various of its devices. This suggests that trusting the local network was a design decision and not an implementation issue manifesting in an isolated device. My N3rd, while not yet popular, it is chosen to showcase a new category of do-it-yourself (DIY) devices. It allows one to connect it to any other device enabling turning on/off that device from the My N3rd mobile app. Increasingly more such projects appear on the market with Arduino-based projects taking the lead. While exciting for users, such devices tend to inherit the problematic trust model and allow an adversary to take full control of ones devices.

In our experiments we consider a mobile adversary that tries to get unauthorized access to the IoT devices. The mobile adversary can perform an attack from an unauthorized phone, or from an unauthorized app on an authorized phone. To test the above cases, we use 2 Nexus phones. The first one is assumed to be untrusted and the second one is assumed to belong to one of the HAN users. We then tried to access the target IoT devices using both phones. Unfortunately we found that the adversary can trivially connect and control all devices. The video demos of our attacks can be found online [13].

| Target Device | Description | # App Installations |
|---------------|-------------|---------------------|
| WeMo Switch   | Actuator    | 100K - 500K         |
| WeMo Motion   | Sensor      | 100K - 500K         |
| WeMo Insight Switch | Actuator | 100K - 500K         |
| My N3rd      | Actuator    | 100 - 500           |

TABLE I: Example devices picked for real-world attack demonstrations.

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6Note that the case of an unauthorized app on an unauthorized phone trivially reduces to the first case we consider.

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Note that a conservative number as people can download the app from alternative Android app markets or from iTunes for iOS devices.
Hanguard is designed to address the issue through bridging network and application level semantics, binding an app’s identity to its traffic to enable a fine-grained access control on IoT devices. In the meantime, it does not modify both software and hardware of these devices, the operating systems of smartphones, and does not make assumptions about the router hardware. For this purpose, our adversary model is focused on the situation where a malicious app is installed on a smartphone device authenticated to the HAN. The adversary is considered to already know the communication protocol used by the victim IoT. We further assume that the smartphone hosting the app has not been compromised at the OS or hardware level, which limits the adversary to the user land, at the app level. Note that though outside our adversary model, Hanguard can also provide coarser-grained protection against guest phones and compromised phones, remote adversaries and more traditional WiFi attacks. To avoid confusion we discuss how this can be done separately (Section VI-B).

Idea and architecture. Figure 2 illustrates the architecture of Hanguard. Our design is partially inspired by software defined networking (SDN) (see [91] for a survey), which separates the network traffic (data) from its management (control). In the meantime, Hanguard is meant to be easily deployed to today’s HAN. Serving this purpose is a distributed security control architecture that includes a controller on a HAN router for policy enforcement and a monitor on the user’s phone for collecting its runtime situation and making access decisions (which are enforced by the router). To avoid changing the mobile OS, the Monitor is in the form of a user-space app. It detects the app making network communication and its compliance with security policies, and then pushes the access permit to the router’s Controller through a secure control channel (Section IV-B). The router utilizes that information to enforce the policy (Section IV-C): only the traffic with a permit from the Monitor is allowed to reach IoT devices.

In essence, this design preserves the data channel within which unmodified information from smartphone apps is propagated to the router, and creates an independent control channel for security decisions. Such a separation, it comes with obvious performance benefits: no extra headers to be processed by the router on a per packet basis in the data channel. It can also guarantee that control information is always transmitted through a secure channel, and allows the router to further enforce policies and ensure, even in periods of heavy congestion, that security decisions are delivered in a reliable manner. In addition, our design allows for a clear separation of tasks: the security policies can be easily managed by the user through a mobile app interface; the router reduces to simply enforcing the flow decisions. This keeps the router as simple as possible and allows for readily updating the security logic with a mere application upgrade.

Policy Model. Using the SELinux [102] type-enforcement (TE) scheme, one tags subjects (e.g. processes) with domains and objects (e.g. files) with types. Then a policy rule can be written (usually by security experts) that specifies which domain can access which type. By default all interactions are forbidden unless a policy rule is in place that allows the interaction. The same concept was introduced for the Android OS as well (SEAndroid [109]) where apps are assigned domains and resources are assigned types. In both SELinux and SEAndroid, one could use the concept of multi-category security (MCS): MCS allows for tagging a subject and an object with one or more category tags. When an SELinux policy is enforced, the system first checks the TE rules to decide whether the interaction is explicitly allowed. Then, the category check is applied to determine whether the subject and object also belong to the same category. Since the MCS check is applied after the TE check, it can only further restrict security. For example it can be used to segregate departments in an enterprise setting. On Android it is used to enforce the multi-user functionality.

Hanguard implements an RBAC (role-based access control) policy model which leverages type-enforcement and multi-category security primitives. It uses them in a unique way to create SELinux-like policy rules, to protect smart-home devices. However, Hanguard does not need security experts to create the policies; policies are generated at runtime and transparently to the user. In particular, the user is only expected to perform simple mappings between a finite set of IoT apps, IoT devices and HAN users. Default policies are automatically created at setup phase to further reduce users’ burden. Hanguard’s access control model parses such mappings and assigns a category tag to each app and its respective IoT device. Further, each IoT device is labeled with a type. Types can be organized in overlapping groups called domains. Each mobile phone is assigned a role and each role can be configured to access a number of domains. For example, the iBaby camera can be labeled with the type “babyMonitor_t”. A domain “cameras_d” can be created to encompass the “babyMonitor_t” type device among others. Lastly, the role of a HAN user’s phone (e.g. “Adult”) that is supposed to be able to access the cameras, can be configured as eligible to access the “camera_d” domain and in extend the “babyMonitor_t” type device. This is analogous to the type-enforcement scheme in SELinux which binds processes
Fig. 3: Hanguard Control Message delivered over TLS: A control message contains the following information: a hash of the user credentials (username, password); the phone’s MAC address; an identifier for the detected flow; the identifier of the requesting app; the policy version used; and a flag indicating flow validation/invalidation.

to resources. Here, the relation between the role and the domain ensures that an untrusted phone (e.g., a visitor’s phone) cannot touch protected devices and even an authorized phone, once compromised, cannot communicate with the IoT devices it is not supposed to talk to (see Section VI). At the same time and orthogonally to the type-enforcement scheme, the iBaby camera and its official app, can be assigned the category “iBaby”. The category here binds a specific app on a phone to the device the phone is authorized to access. For example, the role “Adult” can be configured to access the domain "cameras_d"; while that stipulates that the adult’s phone can control the baby cameras, access is not granted unless the app on her phone and the actual baby camera that it tries to reach are tagged with the same category. Note that more than one category tags can be associated with a domain. This enables the generation of a policy rule which allows an app (subject) to access multiple devices (resources) of the same type.

By default, a phone registered with the HAN is assigned the role “HAN user”, which is allowed to access the “Home” domain. The latter encompasses every newly installed IoT device (which is assigned a unique type). However, the access can only succeed when the app on the phone is given the same category tag as the device it attempts to reach. Such an app-device binding is established when the app is used to configure the device, which is established through a special device, a phone or a PC, that takes the role of an Admin. This role can configure the router, register other user phones, access all domains and update security policies. During a policy update, new domains, roles and access relations between them can be generated. The policy model also handles unregistered phones (e.g., those belonging to visitors), which connect to the HAN as a “Guest”, a role not allowed to interact with the devices in the “Home” domain.

A security policy is stored on both the phone side and the router side. Although its enforcement happens on the router, its compliance check is performed jointly by the router and the phone. The former ensures that only the authorized phone, as indicated by its role, can access the domain involving the device. The latter runs the Monitor to inspect the app and the target device’s category tags and asks the router to let their communication flows go through only when the category tags are the same. This policy model, is extremely flexible and can instantiate a diverse set of relations between users, applications and IoT devices. We describe how individual components of the system work in the follow-up sections.

B. Phone-side Situation Monitoring

In our distributed access-control system, the Monitors are deployed as user-space apps with limited privileges. They are aiming at identifying the subject of a communication attempt, whether the party trying to access an IoT device across the HAN is an authorized one. Such information is delivered through a control message to the Controller module running on the router, informing it the context of the access attempt (since the router cannot see the app initiating the communication), which helps the router enforce appropriate security policies. Note that we designed the system in a way that the workload on the router is minimized, which is important in maintaining the performance level needed for serving the whole local network. More specifically, the Monitor launches at boot time to establish an ongoing secure connection with the Controller module on the router. Through the channel, the situation on the phone is pushed to the router, enabling it to perform a per-flow (instead of per-packet) access control. Further, the security policies (Section IV-A) are broken into two parts: the Monitor checks whether an app is authorized to access a device and asks the router to enforce its decision, while the router implements a phone-level policy check as a second line of defense, which protects the smart-home devices even when a phone is fully compromised (see Section VI).

The communication between the Monitor and the router goes through a TLS control channel. The control message delivered through the channel is in the format illustrated in Figure 3. For example, it includes a hash of the user credentials (username, password), the sender phone’s MAC address, an identifier for the detected flow (IP/port), an identifier for the app making the request, the policy’s version number and a flag indicating whether this flow should be allowed or not. The negative flag is used to invalidate flows (Section IV-C): this happens when a TCP FIN packet is observed for a TCP flow or when the target app stopped sending UDP packets with the same flow signature.

The anatomy of a mobile phone Monitor is depicted on Figure 4. Every registered phone on the HAN, can be assigned roles instantiating an RBAC (Role-Based Access Control) scheme on the router. Furthermore, the phone used to configure the router is by default designated as the Master Controller Node (MCN) and every other phone is designated as the Slave Controller Node (SCN). A HAN user can update the policy through the Policy Update Manager running in her phone’s Monitor. A Monitor accepts policy updates only when it is running on a master node and after verifying its user’s credentials. A distributed Policy Update Service (see IV-C) intermediates policy synchronization and replication in the system. Every connected (reachable) node gets the latest policy replica as soon as it connects to the network or when there is an update. Unregistered devices are automatically assigned the “Guest” role as soon as they connect to the network. Each Monitor has a local in-memory replica of the policy base, that allows it to make decisions for its own traffic efficiently, alleviating the router from further processing. Having the policy
also at the phone side is an important decision in SDN-like systems since it allows for efficient decision making by the Monitors, reduces the bandwidth on the control channel and keeps the routers simple and fast [91]. For example, Monitors need to only send their per-flow decision to the router instead of continuously sending all the mobile OS-situation measurements. In the last case, the number of control messages in the HAN would exponentially increase while the router would need to process all the measurements before making a decision, with severe performance degradation.

**Situation awareness on iOS.** As mentioned earlier, the Monitor is designed to find out which app is talking to an IoT device under protection. Such information, however, is not directly given to a non-system app on both iOS and Android. To tackle this we utilize a new iOS capability that allows developers to proxy network traffic. Once this functionality is enabled by an app and approved by the user, all network packets from all apps will traverse the network stack and instead of being sent through the physical interface to the remote destination, they end up in a virtual interface (tunnel). The tunnel will redirect those packets to the proxy app running the VPN functionality.

iOS offers developers the capability to proxy network traffic with the NEVPNManager APIs. However, blindly tunneling apps’ traffic through the VPN is very expensive, often slowing down the mobile system’s network performance by an order of magnitude. This workflow is illustrated in Figure 5a: when an app makes a network call this would entail, for every packet, a userspace-kernel context switch, traversing the network stack, trapping the traffic through the tunnel interface and context-switching to userspace again to deliver the network packets to the proxying app. Then the proxying app needs to process the network headers (essentially performing layer 3-4 translations) and then resending the packet.

Our solution is to utilize the VPN in a unique way: instead of running the iOS Monitor to proxy the traffic of all apps (through the NEVPNManager APIs), which is expensive, requires a remote VPN server and gives little information about the identity of the app generating traffic, our iOS Monitor uses the NEPacketTunnel Provider APIs with a per-app VPN configuration, to tunnel the traffic only from *authorized apps* (the official apps of the IoT devices), while leaving all other traffic outside the tunnel to avoid unnecessary delays.

Furthermore, over the tunnel, our iOS Monitor does not change the data: it merely acquires packet header information and forwards the packet to its original destination. The whole purpose is that through authenticating itself to the Controller module on the router through TLS and its credentials, the Monitor informs the router that the flow in the tunnel is authorized. Other flows towards the IoT devices from the phone are by default considered illegitimate and will all be dropped at the router. In this way, we can strike a balance between the protection of legitimate IoT management traffic and the performance impact of the security control.

**Situation awareness on Android.** A straightforward way to capture traffic from other apps on Android is to follow a similar process with iOS and utilize the closely equivalent VPNService [51] API, introduced in Android 4.0. However, the implementation of VPN on Android is similar to the one in iOS and would entail similar overheads. To collect the situation information in a more lightweight manner, Hanguard leverages side channels on Android and an approach which results in astounding performance benefits.

The Android Monitor we implemented continuously looks at the procfs file system (see Figure 5b). procfs is a virtual file system which exposes the current status of an Android phone’s kernel internal data structures. Particularly the files proc/net/tcp, proc/net/tcp6, proc/net/udp and proc/net/udp6 disclose the ongoing TCP and UDP connections between the phone and a remote destination, including the source/destination IP addresses of the ongoing connection and its port numbers, the status of the connection etc. The addresses here can be either IPv4 and IPv6 (with the suffix “6”). These connections are also associated with a specific UID that the Monitor can map to an installed app. To minimize operation overheads, the Monitor does not open and parse a file for each access. Instead it just checks the file’s metadata (i.e. the last modified time or mtime in UNIX terms) to determine whether the file has been changed since the last visit. A complication here is that Android often fits an IPv4 address into the IPv6 format before reporting it to the user. Such an address is automatically captured by the Monitor and converted back to the IPv4 form. As an example, consider an app on a phone with an IPv4 address 192.168.1.189

Note that iOS does not reveal to an app the information about other processes through its procfs file system. Before iOS 9, one could use the system call `sysctl` to access such information. This channel has been closed since then.
that connects to an IoT device with the address 192.168.1.32. During the app’s runtime, the connection may not show up in proc/net/tcp but appears inside proc/net/tcp6 instead with 0000000000000000FFFF 0000BD01A8C0 for the source IP and 0000000000000000 FFFF00002001A8C0 for the destination. It is clear that the IPv4 address is enclosed in the 32 least significant bits and the 96 remaining bits are fixed. The Monitor detects the address from its fixed part and converts the rest to an IPv4 format before communicating the app’s identity to the router through a control message. Note that Android suffers from the repackaged apps problem [122]. To address this, the Android Monitor uses a package’s signature to verify apps claiming the identity of policy-controlled apps.

C. Router-side Policy Enforcement

The design of the controller module mainly focuses on synchronizing security policies across all the systems within the HAN and enforcing these policies on the router, as illustrated in Figure 6. More specifically, the module maintains a Master Policy Replica, and runs a Policy Update Service responsible for updating the policies and distributing them across registered Monitors. Further, the Controller module introduces a Per-Flow Decision Cache (PFDC) for keeping the access decisions (on the app level) pushed by the Monitors, and a Garbage Collection Service (GCS) for maintaining the cache. It also hooks on the router’s packet flow for the policy enforcement.

Policy synchronization. It is critical to ensure that all Monitors have a consistent view of the global policy, otherwise flows that need to be blocked might be allowed by the router, or legitimate flows could be blocked. In our system, the MCN node is allowed to change policies only when the HAN router can be reached. In particular, the update is pushed to the router’s Controller module through a write-through model to update the policies both in volatile and persistent storage. After a successful update, the Controller module sends an acknowledgement along with a new policy version number to the MCN node and pushes the new policies to all other reachable Monitors. The Monitors then upgrade their local policy base along to the current version. However, in case a Monitor is not reachable, it could miss the update. As a result, a Monitor could allow an app on its phone to access an IoT device no longer allowed to access, as the app-level decisions are made by the Monitor. To tackle this, the Monitors are designed to asynchronously sense network changes that happen to the phones through the ACCESS_NETWORK_STATE permission (for Android): whenever the phone is disconnected from the network or switched to a different network, the app receives a notification and as soon as the connection to the router is restored, it checks the current policy version and performs an update when necessary. On iOS, this can be done by using the Reachability callback.

Receiving decisions. As mentioned earlier, app-level access control on the router relies on the decision made by the Monitor and delivered to the router through the control channel. To effectively enforce such a decision on a traffic flow, the Controller module is designed to efficiently authenticate and process the control messages from the Monitor to avoid holding up the legitimate interactions with the target IoT device. Specifically, the Controller module maintains TLS connections with the Monitors through a userspace program. When a decision from a Monitor arrives, the router checks the policy version and the sender user’s credentials, and once validated, passes the decision’s flow ID (source IP and port, destination IP and port) to the kernel that updates the PFDC using the flow ID as the key to record the validation/invalidation decision on the flow, which is then enforced by the router. Note that the flow id is used for efficient app-level enforcement. However, data flows are first checked against a phone-level policy which ensures that the flow comes from a valid HAN phone (see Section VI).

Supporting this decision-making process requires an efficient userspace to kernel communication mechanism (for the router). Although this can be achieved through system calls, ioctl calls or procfs files, these approaches are either complicated to implement or unable to handle asynchronous interactions. Our solution employs the netlink socket IPC mechanism for the user-kernel communication, which can be easily built (without changing the kernel) and are asynchronous in nature: it queues incoming messages and notifies the receiver through a handler callback. In our implementation, the callback spawns a worker thread that processes the message and updates the PFDC, either by inserting a valid flow or removing an invalid flow.

The PFDC is loaded at the router’s boot time from its persistent storage. It holds the following information per-flow: the flow ID, the flow validation/invalidation flag, the requesting app and the data last seen time. This cache is used for enforcing app-level policies (whether a specific app is allowed to access a device), for the purpose of enhancing the existing flow-control capability of the router, which cannot differentiate two flows from the same IP and port but produced by different apps. By searching the cache, the router can apply the app-level access decision upon the whole flow, instead for every individual packet, an advantage over deep packet inspection and traffic fingerprinting techniques. To limit the amount of the resource the cache uses (given that the router is a resource-limited

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10In little-endian order, presented using four-byte hexadecimals
device), a Garbage Collector Service (GCS) is run to remove the obsolete records with the oldest data last seen time. Also, a per-phone limit is applied to prevent a Monitor from using too much resource of the cache. Note that this is a measure against DoS. Flow invalidation decisions are made by the Monitors.

**Enforcement.** The router enforces phone-level and app-level policies. For the former, it checks each packet to determine whether it originates from a phone that is allowed to access a particular IoT device. Phones and IoT devices are identified based on their MAC addresses. For the latter it checks with the PFDC cache to determine whether the flow is generated from a valid app.

A technical challenge in implementing the protection is where to place the security control within the existing router infrastructure. On a Linux-enabled system used by the router, once a packet is received, it is put by the link layer into a backlog queue from which the IP layer pulls packets for checksum checking and routing decisions. If the packet is destined for the current machine, it is then passed to the transport layer. If not the packet is forwarded. Apparently, the security control should happen on the IP layer (e.g. in the ip_forward() function). However, a packet might follow a different path within the kernel depending on whether the current system is configured to run as a bridge or a router. For example, in a bridge mode, no layer 3 operation is involved and as a result the aforementioned function will never operate on the packet. Our solution is to place the Controller hook in dev_queue_xmit(), a generic driver function, which ensures that no packet bypasses the check.

To minimize the impact on the communication unrelated to the smart-home devices, the Hanguard-enhanced router quickly inspects each packet it receives to determine whether further attention is needed. Specifically, a TCP flow is considered interesting if its destination MAC address is associated with a protected IoT device. Packets not fitting this description are forwarded on without a delay, and others are first handled according to the phone-level policy (whether the phone can access the IoT device) stored at the router, and then the app-level policy (whether the app can do that) which is based upon the validation flag set by the Monitor. For the packet allowed to go through, its flow’s last seen time is updated to the packet’s arrival time. Hanguard helps its users detect and react to spurious access attempts with its notification mechanism: Hanguard (1) keeps a log, and (2) sends out-of-band notifications to the admin user when a violation or tampering of the policy is attempted.

**V. EMPIRICAL EVALUATION**

We implemented a prototype of Hanguard on top of a TP-Link WDR4300v1 router with a gigabit NIC and a wireless network at the 2.4 GHz band (300Mbps) running OpenWRT Chaos Chalmer with a Linux 4.1.16 kernel, and also Nexus phones running Android 5 (Lollipop) and an iPhone 4S running iOS 9. Our work answers the following research questions:

- **RQ1:** Is Hanguard effective in thwarting attacks from malicious applications?
- **RQ2:** What is the performance impact and resource consumption of the Monitors on the phone side?
- **RQ3:** What is the overall overhead of our system?

**A. Effectiveness**

To answer RQ1 and verify Hanguard’s backward compatibility and its practicality, we performed attacks on real world smart-home devices, including a Belkin WeMo switch, a Belkin WeMo in.sight A1.C, a Belkin WeMo motion and a My N3rd device. The first two devices allow the user to connect to them to any other electronic devices, which then the user can turn on/off through her WeMo app. The Belkin WeMo motion notifies the WeMo app when motion is detected. The My N3rd device can be connected to any other device, enabling remote control of it through the My N3rd app.

**Hypothesis.** A malicious app on a HAN user phone might try to take advantage of the fact that the phone’s role is allowed to access the domain of the target IoT device. However, the Monitor on that phone, will detect the offending flow and determine that the source application has a category different than the one of the target device. Thus it will not push a flow decision to the router, which means the packets on the data plane for that flow will be dropped by the router.

**Experimental Setting.** We performed the following two experiments. (A) First we set up the target IoT devices over the “Vanilla” system (without Hanguard components), and further installed a repackaged version of their legitimate app on the phone to mimic the adversary. (B) Next, we updated the router with H Vanguard-enhanced firmware, and also put our Monitor app on the same phone. Under this protected setting, we repeated the experiment (A), using the phone with the Monitor app to set up the IoT devices.

**Results.** During experiment (A), we found that both the official and the repackaged app on the first phone could see and interact with the target IoT devices. However, during experiment (B)—with our system in place—only the official app on the phone running the Monitor app could communicate with the IoT device and any other attempt was successfully blocked. We conducted the above experiments on all devices listed in Table 1, which confirms the effectiveness of the access control enforced by Hanguard and its backward compatibility. Demos of Hanguard’s success are posted on the project’s website [13].

**B. Phone-side Performance**

To answer RQ2, we focused on the overheads introduced by the Monitor to the phone.

**Monitoring cost on Android.** On Android, the Monitor continuously polls the procfs file system to detect ongoing network connections. Here we report our study on two monitoring strategies and their performance impacts. Specifically, we configured the Android Monitor on a Nexus phone to inspect the procfs file system in different granularity (every 5ms,
10ms, 20ms, 30ms, 100ms). After running for 30 seconds, the Monitor went through every single file line to check the presence of interesting network connections, a strategy called the Naive mode. The approach was compared with another strategy, called the Smarter mode, which first looked at the last modified time of a file before accessing its content. The outcomes of the study are illustrated in Figure 7a. As we can see, the Smarter strategy clearly can poll at a finer granularity (5 ms), given that it reads much fewer file lines compared with the Naive approach (Figure 7b), which is translated to less work per iteration in the common case.

We further looked into the resource consumption of the Monitor. For this purpose, we configured the Monitor to poll at 10 ms and recorded its CPU and battery consumption for both the Naive and Smarter mode. On the same Nexus 5 phone, we also ran Trepn [50] by Qualcomm to collect the baseline power profile of the phone for 30 seconds before running our Monitor app for 2 minutes. Figure 7c illustrates the average battery consumption that can be attributed to the Monitor, and Figure 7d shows the average CPU usage (first 4 bars). To put things into perspective, we compared our Monitor with a popular Antivirus app in scanning mode and the de facto mailing app on Android (Gmail). As we can see from the figures, the power consumption of the naive approach is comparable to an antivirus app performing an expensive operation while the smarter mode’s is comparable with Gmail which is optimized to always run in the background.

### Monitoring cost on iOS.

To evaluate the iOS Monitor’s resource consumption, we used Instruments [19], a performance analysis and testing tool which is part of the official Apple IDE (Xcode [55]). Figure 7d depicts the % CPU utilization that can be attributed to a runtime process, where measurements are indicated with * (last 3 bars): the Monitor when proxying a TCP app that sends 500 messages with payload size equal to one character; the Monitor when proxying an equivalent UDP app; and YouTube while streaming a video configured to auto-select its quality. The figure reflects the fact that the iOS Monitor does a lot of work when proxying TCP traffic: this is expected as TCP is a connection oriented protocol and the Monitor needs to guarantee reliable delivery of the packets. For UDP the Monitor does very little work. In idle mode (not proxying), the Monitor incurred no CPU overhead. Instruments can also report the Energy Use Level of an app at runtime as a value from 0 to 20. In all experiments the reported value was consistently 0/20.

**Decision Latency.** Our Monitor is designed to detect an interesting outgoing connection (or its termination) and notify the router if the connection is allowed by the policy. By the time the data packet from the legitimate app reaches the router, the Controller module needs to have such information available. Otherwise it drops the packet, forcing the TCP layer to retry or the UDP application layer to handle the event. 11 To quantify the impact of the possible delay (the control message arriving later than data packets), we measured the time difference between the first data packet arrival at the Controller Module’s enforcing point and the moment the decision for that flow is stored in the Controller Modules’s flow table (PFDC). We call our new metric the decision latency. In the experiment, we ran a custom app (simulating an authorized IoT app) on the Nexus phone, sending packets of payload of 1 character to a TCP server on a PC connected to the router through Ethernet.

On Android the experiment was performed with the Monitor running in the Smarter mode (with a polling interval of 10, 30 and 100ms respectively). We repeated the experiment 10 times for each interval and report our findings in Figure 8. Note that, since the control message and the flow packets leave the same device almost simultaneously, it is possible for the control message to arrive earlier at the Controller module than the flow packet (see the negative values in Figure 8). As we can see from the figure, the decision latency does not depend on how fast we poll at the Monitor. Other factors, such as link latency and congestion at the router dominate. Also note that this is a one-time cost: once the decision is stored, the router no longer has to wait for it again for other packets in the same flow. On iOS, the decision latency is more predictable. This is because every packet of the target app is routed by the OS through the Monitor. Thus, both the decision and the data packet are send in a more deterministic way. Nonetheless, similarly with Android, the decision is sent through a different channel, which in combination with the router’s different treatment of packets to be forwarded compared with packets destined for its userspace, might cause the data and control packets to be stored and
analyzed respectively by the router in a different order than their sending order.

Detection accuracy. The Monitor’s goal is to detect an interesting flow generated on the phone. For iOS the detection accuracy is 100% since all packets from interesting apps are routed through the VPN the Monitor runs. For the Android Monitor though, the situation is more complicated. For example, an interesting app might quickly set up a socket, send a packet and then close the connection. The Android Monitor’s detection accuracy depends on whether it can catch such events given its polling interval. To answer this question we created a micro-benchmark that includes a TCP and a UDP app connecting to a TCP and UDP echo server respectively. They both stop the communication once the server response is received. Again, we ran the Monitor in the Smarter mode 10 times for each of the following polling configurations: 150ms, 100ms, 30ms and 10ms. We found (see Figure 9) that the 10ms configuration could always detect outgoing TCP and UDP connections.

C. Communication Overhead

To answer RQ3, we performed experiments to illustrate the overall performance overhead of Hanguard, as this can be observed from a target mobile app. We further evaluate the router’s performance in handling non-interesting traffic given the Hanguard security enhancements. We created a baseline by performing our experiments below on the unmodified system (Vanilla). To evaluate Hanguard communication overheads we repeated the experiments with the respective benchmark app not being policy-protected (Unmanaged), and being protected (Managed).

Application latency. We ran the TCP and UDP apps individually, configured to send 100 messages each. Figure 10a depicts the mean latency in milliseconds (ms) for a TCP message and a UDP message for Android. The latency is measured as round trip time (RTT) on the mobile app. In particular we measured the time interval between the API call to send the message and the time that the message is returned by the server and delivered to the application layer. As we can observe, Hanguard introduces negligible latency for Managed apps on Android. In Figure 10b we can see that there is a big increase on TCP packet latency for the Managed apps on iOS. Nevertheless, in practice this is often tolerable, since most devices are actuators and sensors that create mice flows delivering a small amount of information: for example, it is completely imperceptible when the delay for switching a light grows from a few milliseconds to tens of milliseconds. This Figure also reveals an important benefit of our design: the security controls have negligible impact on Unmanaged apps, on both Android and iOS devices, for both UDP and TCP.

Application throughput. To measure Hanguard’s throughput overhead, we use our benchmark apps to transmit a file of 20MB to their server counterparts. We have repeated the experiment 10 times and in Figure 11 we plot the CDF of the throughput for Android and iOS (*). Evidently, Hanguard has negligible impact on throughput for the Android apps and iOS unmanaged apps. Our evaluation also reveals an interesting case: throughput drops significantly for the iOS Managed apps. This happens because the iOS Monitor implementation uses the built in VPN utility of the OS. Thus, it has to inspect every packet for managed apps (see Figure 5a). This is a security, performance trade-off we had to address. We opted in for security. Nonetheless, this will not affect performance of most managed apps in practice: most devices are simple actuators and sensors; the performance penalty will only affect protected iOS-device communications involving real-time streaming services through the HAN. Since obviously this is an edge case, one could handle it differently. For example, when a HAN iOS communicates with such a service, the Monitor could opportunistically intercept traffic instead of checking every packet. Alternatively, in a less security stringent policy, real-time streaming services could get only phone-level protection.

12 A mouse flow is a flow with a short number of total bytes sent on the network link.
which will eliminate all iOS overheads.

VI. SECURITY ANALYSIS

A. App-level Attack Scenarios

Access from unauthorized HAN user phone. An app on an unauthorized HAN user phone might attempt to access an IoT device. Even if the app’s category matches the IoT device’s category, the Monitor on that phone will detect the outgoing flow and determine that the host phone’s role cannot access the domain which encompasses the target IoT device. Thus it will not push a flow decision to the router for that app and packets on the data plane for that flow will be dropped by the router.

Access from unauthorized app on an authorized HAN user phone. (a) A malicious app on a HAN user phone might try to take advantage of the phone rights and access an IoT device. However, the Monitor on that phone, will detect that the source application has a category different than the target device. Thus it will not push a flow decision to the router, and the malicious packets will be dropped by the router. (b) A repackaged app on Android could use the same package name as a Hanguard category-tagged app. However, the Android Monitor uses the package signature to verify an Android app. Therefore, the Monitor detects the discrepancy, notifies the user and does not authorize the data flow.

B. Beyond the app-level adversary

WPA2-PSK authentication and Hanguard network partition. On a typical WLAN node, once a subnetwork is created it can be configured to use a Service Set Identifier (SSID) and the WPA2-PSK security protocol. WPA2-PSK derives a unique pairwise transient key to encrypt the communication traffic between individual nodes on a HAN and the router. However, all keys are derived from the same SSID and a secret passphrase shared across all the nodes. As a result, a compromised phone could potentially use the key to directly connect to an IoT device, bypassing the router-level protection. To address this threat, Hanguard partitions the HAN into two default subnetworks, each with their own SSID/passphrase pair, one for user phones, PCs and laptops, and the other for IoT devices. This ensures that even a fully compromised phone cannot acquire the secret key used by smart-home devices.

Access from unauthorized authenticated guest phone. (a) A guest phone’s role is only allowed to access the unprotected domain. If the target IoT device’s type is in another domain, the router will reject the offending packets. (b) A guest phone might try to claim the identity of one of the HAN Monitor’s to alter the policy rules. Since the guest phones are in a different local network and use different keys, the router will not accept rules from those phones. Further, a guest phone will not be able to authenticate to the router controller module, since it lacks both the client certificate and the user credentials. Lastly, Hanguard uses static IPs associated with phones/devices MAC addresses during setup by the admin role. Any attempt to claim a reserved IP (arp-spoofing) or MAC address (MAC-spoofing) is validated through the control channel and the admin user is notified out-of-band.

Compromised HAN user phones. In this case, Hanguard can still guarantee phone-level access control. (a) The phone might attempt to surreptitiously access an IoT device. Assuming it acquires the user credentials and the Monitor certificate, it can try to push a rule to the router to allow its flow. However, the router detects that the rule comes from a device whose role is not allowed to access the type of the target device. It rejects the rule and notifies the admin user. (b) The phone might attempt to update the policy in its favor. An attempted policy update by a non-admin device will be rejected and the admin will be notified. Even if the admin device and its user credentials are compromised and a policy update is pushed, the admin user will be notified. Thus she can revoke the update and take action. (c) The phone, might try to flood the flow decision cache. This would force the GCS service to retire older flows, essentially invalidating benign flows and causing denial of service. To tackle this, we rate limit the flows a particular device can create. If that limit is surpassed, the device is penalized by having the router dropping all its packets for a few minutes. During that time, no flow entries will be added in the decision cache originating from that device. Furthermore, Hanguard triggers its notification mechanism.

Remote adversary. Commonly, an IoT device behind the NAT initiates a connection to its cloud, through which the cloud learns the device’s external IP and port. However, if this information is exposed to an unauthorized party, that party can gain unfettered access to the device [42], [85], [95], [106]. To shut down this exploitable channel, Hanguard by default configures the router to a port-restricted cone NAT, which ensures that only the flows from the remote IP/port pairs contacted before by a local device can reach that device. Note that this NAT mode is supported by most smart-home devices on the market [29], [28], [52], [48].

VII. DISCUSSION

HAN users smartphones OS integrity. Our application-level enforcement assumes that HAN user phones are not compromised. Preventing phone compromises is out of the scope of this work since other solutions already exist and even deployed on commodity smartphones [96], [117], [120].

![Fig. 11: Application-level throughput (TCP).](image-url)
For example, SELinux for Android [110] uses mandatory access control to ensure that even compromised system processes are restricted, and is deployed on all Android phones with version 4.4, and higher (more than 60% in 2015 [44]). Most Android phones are equipped with ARM processors [57] with TrustZone [56] which can be utilized for solutions stemming from the trusted computing domain. TZRKP [62] is a real-time kernel protection technique deployed on Samsung Galaxy phones that ensures the kernel integrity using the ARM TrustZone secure world. iOS devices have the Secure Enclave, a secure co-processor that is used to guarantee secure boot [58]. However, even if a user device is compromised (and in the case of all guest phones), Hanguard can guarantee phone-level protection (Section VI-B). Furthermore, Hanguard helps its users detect spurious access attempts by (1) keeping a log, (2) sending out-of-band notifications to the admin user when a violation of the policy is attempted.

Switching Between Information Gathering Approaches. iOS follows a far more stringent approach than Android in isolating processes. In fact our Android solution for traffic monitoring does not work on iOS. Instead we utilize Apple’s NEPacketTunnel Provider API with a per-app VPN configuration. The latter requires an MDM (Mobile Device Management) server: the router vendor will need to enrol their users’ iOS devices and push an over-the-air (OTA) configuration profile on the phone, just like the cell phone carriers (e.g. AT&T, T-mobile etc.) do. This process is already mature and streamlined for users who just need to accept the configuration. Apple does offer the non-enterprise NEVPNManager API but that would entail Hanguard iOS Monitors proxying traffic not only from a selected set of apps but from all apps, imposing the overheads we demonstrate in Section V for both unmanaged and managed apps. In our prototype we opted for security and runtime performance in the expense of an initial bootstrapping usability burden, that allows us to selectively proxy traffic only from a handful of apps when used in the HAN environment. Our work illustrates how such capabilities can facilitate novel solutions on the iOS platform. Also note that any of the two aforementioned techniques can be used in practice with Hanguard iOS Monitors. Hanguard’s design, allows router vendors to readily switch between monitoring techniques with a mere application update. Similarly, if access to the Android procfs as a whole is forbidden in the future (not a straightforward decision since this would break a lot of legitimate apps), Hanguard can switch to a VPNService-based Android Monitor by merely pushing an app update.

Communication through cloud. Some apps still go through the cloud during the communication phase, even if they are on the same HAN as the device. Hanguard’s RBAC can be applied to those apps as well by extending the NAT checks. In particular the Monitors can detect an app on a user phone contacting its respective cloud service and notify the router. Using the traditional port-restricted cone NAT, Hanguard allows the traffic from validated external IoT domains to reach their respective IoT devices as long as the connection was initiated from the IoT device itself. In this case, Hanguard can further utilize the information received from the Monitor, and allow the remote traffic only if the following also hold true: (a) the role of the phone generated the traffic to the device’s IoT cloud is allowed by the policy to access that device, (b) the category of the app matches the category of the target IoT device and, (c) the traffic came within a time limit since the receipt of the control message (e.g. 1 sec). The last is needed to tackle the fact that someone could try to bypass the system while an accepted role also sent a remote command.

VIII. RELATED WORK

IoT attacks. Recent works have demonstrated attacks on IoT devices [121], [114], [100], [108], [75], [107]. Fernandes et.al. found vulnerabilities on SmartThings’ applications [75]. Their work focuses on a specific IoT hub that can integrate third-party IoT devices. Our work presents a solution applicable to an infrastructure that exists in almost all households with IoT devices. [114], [100], revealed vulnerabilities on the Philips Insight, iBaby baby cameras and Belkin devices. However they consider an adversary on a separate device. [107] considers an intricate mobile adversary which colludes with a cloud. We illustrate that the mobile adversary can succeed with minimal effort. All reported attacks further motivate the need for practical smart-home defenses.

Side-channels on Android and network monitors. Several works focused on acquiring information for other processes using side-channels on Android [123], [125], [84], [121], [121] also utilized side channel information for defence purposes, avoiding system-level modifications. [92] used the VPN service on Android for passive monitoring of a selected set of mobile apps to collect user traffic information for analysis. However, it redirects all packets to a server that further routes the packets. This entails privacy concerns which we avoid by implementing the routing functionality locally.

Access control. There have been various works on home access control which we classify in three major areas: surveys [79], [118], [73]; access control systems [59], [71], [89], [94], [108], [76]; and user studies for usable policy specifications [90], [97]. More relevant to our work is the second. Nonetheless, most of these systems assume a clean-slate design where the OSes of participating nodes can be modified. Our solution is backward compatible: it requires just a software upgrade on the Home’s router and downloading an app on the phone. Other work focused on access control enforced on the mobile phones [111], [64], [72]. Demetriou et. al. [72] enforced local policies to control access to personal devices while our target is to enforce a distributed policy on shared devices.

IDS and Firewalls. Work on intrusion detection systems (IDS), personal and application firewalls [70], [86], [60], [67], focuses either solely at the host or at a network node, or only at the network layer. Our solution works in a distributed manner, consolidating application level semantics from hosts, and
network level information from the network node. Furthermore, we do not require experts to set up policies.

IX. CONCLUSION

In this work we presented Hanguard, a system that can enforce access control policies in a HAN among user phones and IoT devices. Hanguard uses a new software-defined networking (SDN) approach applied on home area networks using mobile phones as monitors: it employs situation awareness on users’ phones through a userspace Monitor app that detects whether an authorized app is establishing a network flow with a target IoT device; Monitors push decisions to the HAN router bridging the gap between network and application-level semantics. This technique allows the router to enforce fine-grained access control based on a global policy protecting access to HAN IoT devices. Hanguard does not require mobile OSes modifications, any IoT device modifications, or new router hardware. It is backward compatible with the existing HAN infrastructure, and was implemented and evaluated in a realistic HAN setting, verifying both its practicality and effectiveness.

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[5] Belkin netcam. http://goo.gl/60fikg.
[6] Belkin wifi netcam video stream backdoor with unchangeable admin/admin credentials. http://goo.gl/XnzmwAk.
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[25] Mobile malware, unpatched android devices are increasing problems say studies. http://goo.gl/EUGmDc.
[26] microccoffee.com. http://goo.gl/XVn7hT.
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[40] ring.com. https:// goo.gl/3EXF6s.
[41] Samsung family hub refrigerator. http://goo.gl/ddwxbX.
[42] shodan.io. https:// goo.gl/UUL10K.
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As the IoT industry matures, more and more devices add local WiFi connections to avoid the cloud availability requirement and unnecessary latency. In our work we compared the

![Fig. 12: Wearables functionality sub-categorization.](image_url)
App Selection. Our IoT product collection (see Section III) resulted in 223 products having apps on Google Play. However, a lot of apps can control multiple products. For example, the WeMo app can control at least three Belkin WeMo products. In particular, we found 92 unique Android apps on Google Play. Note also that part of these 92 apps, are apps that control wearables such as smartwatches and fitness trackers. Thus we manually went through the 92 apps and selected only those that connect to smart-home devices. This resulted in 55 unique smart-home apps. Our collection is conservative: while it does not yield a complete set of smart-home Android apps, it ensures that the selected apps are related to WiFi smart-home devices. This is important since our null hypothesis is specific to devices that connect to the HAN.

App Analysis. See Section III-B.

Results. Unfortunately, we found that smart-home apps tend to trust the local environment which exposes them to attacks from mobile adversaries—9/22 (41%) apps with local WiFi connectivity perform no authentication when in the HAN. Table II lists the 55 IoT systems we examined for our statistical significance test. This highlights the need for a solution which is independent of IoT vendors and application developers practices. Hanguard on top of its role-based management capabilities, also offers protection for IoT devices.
# TABLE II: IoT apps selected for trust model analysis. Y = YES; N = NO; ? = Undetermined.

| No | PACKAGE NAME                        | CATEGORY                          | # Installations | DECOMPILED | OBFUSCATED | LOCAL WIFI | LOCAL AUTH |
|----|-------------------------------------|------------------------------------|-----------------|------------|------------|------------|------------|
| 1  | is.yranac.canary                    | TOOLS                             | 100K - 500K     | N          | -          | -          | -          |
| 2  | com.netgear.android                 | VIDEO PLAYERS & EDITORS            | 100K - 500K     | Y          | N          | -          | -          |
| 3  | com.homeboy                         | LIFESTYLE                          | 1K - 5K         | Y          | N          | -          | -          |
| 4  | com.belkin.android.androidbelkinnetcam | VIDEO PLAYERS & EDITORS             | 100K - 500K     | Y          | N          | Y          | Y          |
| 5  | com.petcube.android                 | LIFESTYLE                          | 10K - 50K       | Y          | N          | -          | -          |
| 6  | com.blacksmac.piper                 | LIFESTYLE                          | 50K - 100K      | Y          | Y          | Y          | Y          |
| 7  | ibabymonitor.main                   | TOOLS                             | 10K - 50K       | Y          | Y          | Y          | ?          |
| 8  | com.philips.cl.insight              | LIFESTYLE                          | 50K - 100K      | Y          | Y          | Y          | Y          |
| 9  | com.chamberlain.myq.chamberlain     | LIFESTYLE                          | 100K - 500K     | Y          | N          | -          | -          |
| 10 | com.garagego                        | TOOLS                             | 1K - 5K         | Y          | N          | -          | -          |
| 11 | com.skybell                         | LIFESTYLE                          | 10K - 50K       | Y          | N          | -          | -          |
| 12 | com.orvibo.kepler                   | LIFESTYLE                          | 1K - 5K         | Y          | N          | -          | -          |
| 13 | com.kornersafe.secure.agg           | LIFESTYLE                          | 1K - 5K         | Y          | N          | -          | -          |
| 14 | com.lifs.lifs                       | LIFESTYLE                          | 100K - 500K     | Y          | Y          | Y          | N          |
| 15 | com.philips.lighting.huie           | LIFESTYLE                          | 500K - 1M       | Y          | Y          | N          | -          |
| 16 | com.alture_energy.escort            | TOOLS                             | 1K - 5K         | Y          | N          | -          | -          |
| 17 | com.honeywell.mobile.android.totalt.comfort | LIFESTYLE | 500K - 1M | Y | N | - | - |
| 18 | com.ecobee.athernamobile            | LIFESTYLE                          | 50K - 100K      | Y          | N          | -          | -          |
| 19 | com.honeywell.android.lyric         | TOOLS                             | 10K - 50K       | Y          | N          | -          | -          |
| 20 | com.wifislag.android2               | TOOLS                             | 1K - 5K         | Y          | N          | -          | -          |
| 21 | com.tado                            | TOOLS                             | 10K - 50K       | Y          | N          | -          | -          |
| 22 | com.albraha.sprinklers              | TOOLS                             | 5K - 10K        | Y          | N          | Y          | Y          |
| 23 | com.icorservo.blossom               | LIFESTYLE                          | 1K - 5K         | Y          | N          | -          | -          |
| 24 | com.skydrop.app                     | TOOLS                             | 5K - 10K        | Y          | N          | -          | -          |
| 25 | com.hydravve.android2_2             | PRODUCTIVITY                      | 5K - 10K        | Y          | N          | -          | -          |
| 26 | com.rachuo.iro                      | LIFESTYLE                          | 10K - 50K       | Y          | N          | -          | -          |
| 27 | bc.snapppee.mobile.android          | LIFESTYLE                          | 10K - 50K       | Y          | N          | -          | -          |
| 28 | com.smart_me                        | TOOLS                             | 1K - 5K         | Y          | N          | -          | -          |
| 29 | com.eyesight.simplecue              | ENTERTAINMENT                     | 1K - 5K         | Y          | Y          | Y          | ?          |
| 30 | com.amazon.dee.app                  | MUSIC & AUDIO                     | 1M - 5M         | Y          | N          | -          | -          |
| 31 | com.myn.3rd.n.dremote               | TOOLS                             | 500 - 1K        | Y          | N          | Y          | N          |
| 32 | com.sensibo.app                     | TOOLS                             | 5K - 10K        | Y          | N          | N          | -          |
| 33 | net.wifisocket.advancedlumomcstabs  | LIFESTYLE                          | 100 - 500       | Y          | N          | -          | -          |
| 34 | ins.tuka.android_app                | SHOPPING                           | 1K - 5K         | Y          | N          | -          | -          |
| 35 | com.dnm.leos.phone                  | MUSIC & AUDIO                     | 100K - 500K     | Y          | Y          | -          | -          |
| 36 | com.musaic.musaiccontrol            | MUSIC & AUDIO                     | 1K - 5K         | Y          | N          | Y          | ?          |
| 37 | com.beep.android                    | MUSIC & AUDIO                     | 1K - 5K         | Y          | N          | Y          | N          |
| 38 | com.wifiaudio                       | MUSIC & AUDIO                     | 5K - 10K        | Y          | N          | N          | N          |
| 39 | com.roika.remote                    | ENTERTAINMENT                     | 5M - 10M        | Y          | Y          | Y          | N          |
| 40 | org.qqproject.example.EezecSync     | VIDEO PLAYERS & EDITORS            | 100 - 500       | Y          | N          | -          | -          |
| 41 | com.mireon.mireon5                  | LIFESTYLE                          | 50K - 100K      | Y          | N          | Y          | ?          |
| 42 | com.lutron.nsw                     | LIFESTYLE                          | 10K - 50K       | Y          | N          | Y          | Y          |
| 43 | com.osram.lightify                  | LIFESTYLE                          | 10K - 50K       | Y          | N          | Y          | N          |
| 44 | com.scoutalarm.android              | TOOLS                             | 1K - 5K         | Y          | N          | -          | -          |
| 45 | com.sybas.riot.otmobile.android      | LIFESTYLE                          | 500 - 1K        | Y          | N          | -          | -          |
| 46 | com.alit.lymobile                   | LIFESTYLE                          | 500 - 1K        | Y          | N          | -          | -          |
| 47 | ins.common                          | TOOLS                             | 10K - 50K       | Y          | N          | Y          | N          |
| 48 | com.wigwag.wigwag_mobile            | LIFESTYLE                          | 100 - 500       | N          | -          | -          | -          |
| 49 | com.irisbyloves.iris.timeapp        | LIFESTYLE                          | 10K - 50K       | Y          | N          | -          | -          |
| 50 | com.webee.mywebee                   | LIFESTYLE                          | 1K - 5K         | Y          | N          | -          | -          |
| 51 | com.codecatelier.homee.smartphone   | PRODUCTIVITY                      | 5K - 10K        | Y          | N          | Y          | ?          |
| 52 | com.zonoff.diplomat.staples        | LIFESTYLE                          | 5K - 10K        | Y          | Y          | Y          | ?          |
| 53 | com.revolv.android.app              | -                                 | -               | NOT FOUND  | -          | -          | -          |
| 54 | com.amazon.storm.lighting.client.aosp | TOOLS | 1M - 5M | Y | N | Y | ? |
| 55 | com.belkin.wemoandroid              | LIFESTYLE                          | 100K - 500K     | Y          | N          | Y          | N          |