Abstract

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| --- |
| Research Statement: How have manufacturers of IoT / smart home devices have addressed the increasing concerns of digital privacy and product security |

With the ever-growing adoption of convenient and user-friendly Internet of Things devices, more and more objects around us make their way onto the internet, requiring the web for one reason or another. Despite the unknown nature of communication and limited transparency of data, such privacy concerns are often overlooked in exchange for convenience. This paper audits the Roborock S6 robotic vacuum cleaner to assess its internal operations and network activity behaviour, as to investigate any potential vulnerabilities that may render the device unsafe or insecure.

A combination of dynamic and static binary analysis methods were performed to assess the security of the device, and network activity was inspected to verify the contents of network traffic. Investigation results revealed discrepancies in both the security of the product, and the privacy of user data pertaining to authentication credentials. Notably, a novel command injection exploit was proposed, and suggestions were made to better improve the device’s security and privacy.

Acknowledgements

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| --- |
| sonder (noun) the realisation that each random passerby is living a life as vivid and complex as your own |

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Table of Abbreviations

|  |  |  |
| --- | --- | --- |
|  | **Expansion** | **Meaning** |
| **C2** | Command and Control | Remote action management |
| **DUT** | Device Under Test | Relating to the specific device being tested |
| **eMMC** | Embedded Multimedia Card | Onboard storage |
| **HSTS** | HTTP Strict Transport Security | Network security policy |
| **IoT** | Internet of Things | Classification of network-connected devices |
| **IP** | Internet Protocol | Network communication protocol |
| **IPC** | Inter-Process Communication | Data exchange between programs in a system |
| **MAC** | Media Access Control | Unique network device identifier |
| **MITM** | Man In The Middle | Intercepted communication |
| **MQTT** | Message Queue Telemetry Transport | Network communication protocol |
| **NIC** | Network Interface Card | Hardware to connect a device to a network |
| **PII** | Personal Identifiable Information | Data that could identify an individual |
| **PoC** | Proof of Concept | A demonstration to prove a concept / theory |
| **SDK** | Software Development Kit | Building blocks for software interoperability |
| **SoC** | System on Chip | An entire system integrated into a single chip |
| **SSID** | Service Set Identifier | Wi-Fi network name |
| **SSL** | Secure Sockets Layer | Network security protocol |
| **TLS** | Transport Layer Security | Network security protocol |
| **UART** | Universal Asynchronous Receiver/Transmitter | Hardware communication protocol |
| **UGC** | User Generated Content | Data created by the user |
| **WEP** | Wired Equivalent Privacy | Network security algorithm |
| **WPA** | Wi-Fi Protected Access | Network security algorithm |

# Chapter 1 | Introduction

Consumer grade Internet of Things (IoT) devices have become widely adopted with continuously growing demand. With demand growing by 12% each year (Research & Markets 2021), this AU$130bn industry has cordially invited thousands of households to invest in smart devices such as light bulbs, fans, televisions and fridges. Giving the abundance and affordability of these products, IoT devices have become an integral part of many homes, where 4 in 5 consumers would be more inclined to choose a property over another given the presence such technologies (Brown 2015).

Although convenient, these devices come with hidden costs and risks. Behind the seemingly ‘simple’, ‘smart’ and ‘secure’ product features that attract consumers lie a hidden complex network of services and devices, where functionality is often obscured and private. Without the transparency of what data is being sent, and of where that data is being sent to, consumers inevitably pay for convenience with not only their money but with their privacy and security (Miralem, Nejra et al. 2019)

Whilst manufacturers and vendors claim to be secure and/or confidential in how they treat UGC and PII, it is evident from various incidents that we cannot completely trust such claims. From leaked Facebook user data (Abrams 2021), to rumours of corporations monetising user data without consent (Jones 2017), there lies an equal need for consumers to understand the terms of service to which they agree to, but additionally for companies to be audited against those very same terms of service.

The infrastructural security and product security of IoT devices must also be scrutinised, given the rapid product lifecycle of IoT developments (Giese 2021). As security is often not a sellable feature in contrast to new products and most fallibly – convenience, proper and wholistic security precautions are often overlooked by companies who are more concerned with profits. Consequently, the prevalence of malicious actors in the cyberworld is alarming, where the overall lack of security awareness between consumers invites target devices to be easily accessed with default passwords or through unpatched vulnerabilities[[1]](#footnote-2).

Given the black-box nature of IoT network communications where there is little transparency about the functionality and usage of IoT devices beyond their advertised description, there is a need to shed light unto the privacy and security of these devices. **This thesis aims to detail** **how manufacturers of IoT / smart home devices have addressed the increasing concerns of digital privacy and product security**. Specifically, we audit the Roborock S6 robotic vacuum cleaner to assess its internal operations and the nature of data that is transmitted, as to verify manufacturer claims, and investigate potential vulnerabilities that render the device insecure.

We first study further motivations behind auditing the privacy and security of IoT systems, then review existing research and methods that comprise the current state of the art of IoT security and privacy research. Finally, we detail the work performed in this thesis and discuss the contributions and conclusions, providing suggestions to further the security and privacy of IoT devices.

Summary of Major Contributions

This thesis critically analyses the security and privacy of the Roborock S6’s firmware and network communications. A list of major contributions and actionable findings are as follows, by decreasing order of severity and importance.

**Data Persistence**

File persistence tests were conducted to test the retention of data during the following scenarios: firmware upgrade, factory reset, device disassociation (unpairing). It was observed that no data was cleared when a device was unpaired, raising concerns regarding data privacy. Methods were proposed to persist data during firmware upgrades and factory resets.

**Privacy Policy**

The privacy policy of the vacuum cleaner data was assessed and revealed that a statement regarding the locality of wireless credentials was non-compliant, as the credentials were found within uploaded log data.

**Pairing Security**

The pairing process of the device was observed and revealed that wireless credentials were transmitted in plain text over an unsafe medium (wireless network with open / no security), despite IoT ecosystem vendor guidelines to require a secured means of communication.

**Product Security**

Security assessments were performed on the programs in the Roborock S6 firmware to evaluate the security of the device. Whilst most programs were secure, a novel command injection vulnerability was discovered in the Android Debugging Bridge implementation. A proof of concept was created and disclosed to the vendor.

Upgrade analysis revealed that the vendor has made non-trivial effort to fortify their software against vulnerabilities and limit unauthorised access to the device.

**Network Behaviour**

The nature and content of network traffic generated by and received from the Roborock S6 was analysed to create a connection map of device communications, and a heatmap of network activity. A Manufacturer Usage Description profile (RFC 8520) was created for the device to better describe its expected traffic behaviour and provide a means to mitigate foreign traffic. The IPv6 capability of the device was also tested, drawing conclusions that possible IPv6 related issues were benign.

# Chapter 2 | A Background on IoT

## The Call to Action

The consumer market has experienced a large influx of IoT devices, largely attributed to the presence of IoT manufacturers who offer white-label partnerships with resellers to provide “custom” products. Through these partnerships, vendors buy into the IoT manufacturer’s ecosystem - namely the product itself, the companion smartphone application, and the cloud infrastructure supporting network communications - all without requiring vendors to possess any knowledge or understanding of how to design, develop nor manufacture the IoT products that they sell.

Concerns are raised regarding the privacy and ownership of user data that is transmitted, as vendors themselves are often not in control of what information is transmitted nor of how that information is used – for example if the microphone data of a surveillance camera was used to determined advertised products related to the conversation. The lack of control over information is a potentially serious concern, as vulnerabilities within an IoT infrastructure would endanger customers from other vendors under the same infrastructure. Furthermore, the lifetime of a vendor business is not guaranteed. With the constant opening and sunsetting of IoT vendors, the closure of the business from which an IoT product was purchased from might eventually render the device inoperable.

In the event that an IoT infrastructure suffers downtime or service instability, all white-labelled products too will also be affected. Great trust must be placed in the infrastructure’s availability and reliability. In conjunction with aforementioned privacy and security concerns, many concerned users have turned to internet-less and self-hosted automation systems such as *HomeAssistant* and *OpenHAB*. As evident in later reviewed works, concerns for privacy and security have been a driving force for developers and hackers to research and develop software to replace the internet-dependent stock software, effectively decoupling devices from vendor services.

## About the Product

Roborock is a Chinese company founded in Beijing that develops robotic cleaning appliances for households. In 2014, partnering with Xiaomi shortly after the opening of their business, the company released a line of both affordable and premium smart robotic vacuum cleaners, with their first iteration the “*Mi Home Robotic Vacuum Cleaner*” being released in Sep 2016. They have since released twelve other robotic vacuum cleaner models, each model offering new and improved features. Despite having released 13 different products, only one security vulnerability has been publicly disclosed[[2]](#footnote-3), raising concern about the company’s security.

In June 2019, Roborock released their flagship Roborock S6 vacuum cleaner. Featuring an *Allwinner R16* SoC (ARM architecture), it is powered by either the Tuya Smart or Xiaomi Cloud infrastructure, both market leaders in the consumer IoT industry. Despite being released three years ago, the Roborock S6 vacuum cleaner is still widely popular and actively maintained by Roborock. This device will be the DUT (device under test) in this thesis.

# Chapter 3 | Current State of the Art

## Broad security study of Tuya-based devices

The security research group Vtrust (2018) analysed a line of white-labelled IoT product revisions based on the IoT manufacturer Tuya to identify common security vulnerabilities. Despite vendor claims of ‘military-grade security’, basic packet logging of network activity concluded that “the analysis of the ‘smart’ devices using this basic platform is generally frightening”, with “*serious […] shortcomings*”. It was revealed that various PII, encryption keys and the device’s serial number (used to specify a device during remote commands) were insecurely transmitted over the network, allowing a user on the same wireless network to eavesdrop on the communication. Furthermore, during the initial setup and pairing of the IoT device, wireless credentials were also insecurely transmitted in plain text, allowing wireless network credentials to be observed.

Vtrust commented on the dangers of vendors selling white-label products, where anyone could become a so-called ‘IoT company’ regardless of whether they had “in-depth technical knowledge of IoT or IT security”. As a result of the hands-free approach to security and privacy for both direct and indirect customers of the IoT platform, concerns were raised regarding the ease of distributing maliciously modified devices, where firmware could be tampered with during any stage within the supply chain.

It is worthwhile to recognise that most custom firmware releases or “hardware hacks” originate from the desire to decouple hardware from online and official cloud services. These ventures effectually disconnect internet-reliant devices from the cloud, and limit their connectivity to a local server where communications are transparent and minimal.

As a result of many Tuya-powered devices sharing the widely popular *Espressif ESP8266 SoC[[3]](#footnote-4)*, Vtrust was able to exploit discovered vulnerabilities on multiple products to perform over-the-air upgrades of custom firmware (e.g. [*ESPhome*](https://esphome.io/), [*Tasmota*](https://tasmota.github.io/docs/)). An automated flashing tool ([tuya-convert](https://github.com/ct-Open-Source/tuya-convert)) was released, allowing consumers to easily integrate these devices with local home automation software such as [*HomeAssistant*](https://www.home-assistant.io/). As a result of Vtrust’s findings, the overall security posture of modern Tuya-powered devices has since improved[[4]](#footnote-5), with implementations of local flash memory encryption and firmware signing measures during over-the-air firmware upgrades.

Vtrust’s technical findings offer insights into methods of network-level security assessment highlighting how easily an individual could start their own IoT company, and the possibility of reselling devices with modified firmware with malicious intent. In this thesis we perform similar network security assessments through means of analysing packet captures to determine if data is weakly or insecurely transmitted.

## Broad security study of Xiaomi-based devices

Giese (2019) performed a security assessment over a broad range of Xiaomi’s IoT products to examine the overall security of the Xiaomi ecosystem. Through different software injection and hardware fault injection techniques, Giese obtained shell access into various Xiaomi-powered devices. It was concluded that due to the enormous size of Xiaomi’s ecosystem, it was difficult to enforce global security policies between the different vendor-provided plugins that continued to support deprecated functions and APIs that were still being used by legacy devices. Out from this research, a [*cloud emulator*](https://github.com/dgiese/dustcloud)*[[5]](#footnote-6)* was built, allowing for complete offline functionality and control over a large range of Xioami devices without requiring internet connectivity. This research also paved the way for other third-party, privacy-focused, vacuum cleaner remote applications to developed, such as [*Valeduto*](https://github.com/Hypfer/Valetudo).

He concluded that Xiaomi indeed treats their security concerns seriously, given their quick responses to reported security incidents and vulnerability reports. In this thesis, we too will assess the security and privacy postures of IoT devices on the business-level.

It should be noted that Giese briefly assessed the security of the Roborock S6 vacuum cleaner in his study. Whilst Giese did perform a security analysis of the device under test, this thesis was performed as an independent study. With the exception of Giese’s work to obtain initial shell access, all other similar methods performed, findings and observations are coincidental. This thesis furthers previous studies as it additionally audits the state of privacy of the device.

## Security study of smartphone applications

Jmaxxz (2016) investigated the security claims of a smart doorlock which had boasted in its bank-grade security, and superiority over conventional lock-and-key systems. These claimed were however invalidated, as flaws within the smartphone application were discovered which allowed control over the lock settings, amusingly only being protected by client-side checks. Consequently, modified request payloads containing elevated authorisation claims would be naively accepted by the server, allowing lock settings to be modified by a guest or other user. Furthermore, various debugging menus were present in the production version of the smartphone application, allowing certificate pinning protections to be subverted. In addition, the privacy of the user was also questioned, as it was observed that door lock events and other identifiable information were being transmitted to a logging endpoint.

The vulnerabilities in the smart doorlock’s own product security highlight the importance to verify any claims that manufacturers may advertise. This study serves as an excellent example of a failed access control system, where elementary methods of request tampering and hardcoded keys allow for arbitrary privileged control of a device. Subversion of HTTP Strict Transport Security (HSTS) and certificate pinning policies through system-wide tools[[6]](#footnote-7), per-application patching[[7]](#footnote-8) or accessible debug menus furthermore underlines that certificate pinning should not be relied upon to verify identity nor authority.

## Analysis of similarities in IoT firmwares

Costin, Zaddach et al. (2014) performed a broad static firmware analysis over a large number of firmware images to identify common patterns and similarities between product vendors. During the analysis of the 693 images, 38 new vulnerabilities were discovered, some of which were present in the majority of images. Many hardcoded keys and credentials were also discovered that could render the IoT device or its infrastructural service vulnerable. To facilitate the similarity analysis of firmware images, where per-byte analysis techniques are nonsensical, tools like [binwalk](https://github.com/ReFirmLabs/binwalk), [ssdeep](https://github.com/ssdeep-project/ssdeep), and [sdhash](https://github.com/sdhash/sdhash) were employed - which helped to facilitate file exploration relative to their file type and architecture. To compare versions of the same binary across different firmwares, a tool called [BinDiff](https://www.zynamics.com/software.html) was used, which would compare the similarities and differences in assembly code and call graphs.

A large proportion of images shared similarities in code execution graphs, indicating that many vendors had simply reused and repurposed sample code (often available as part of the SDK from a SoC vendor or IoT framework). Whilst sample code itself is not often vulnerable, given the commonality of other vulnerabilities, concern is raised as to the vendor’s technical capability and understanding of IoT systems and of security. The tools and methods to perform this firmware study are transferable to the scope of this thesis, where static analysis of executable programs can be used to identify vulnerabilities or potential malicious modifications to existing software.

## Side-channel application of LIDAR sensor measurements

As more and more IoT devices become online and sensor data is transmitted around the world, there are growing concerns to thoroughly investigate the extents of what data can be retrieved from the sensors. Given that the outputs of Light Detection and Ranging (LIDAR) sensors are reflected intensity values and distance measurements, Wei, Wang et al. (2015) developed a method to translate the intensity readings from the LIDAR sensor back into audio signals, when the LIDAR sensor was directed towards a surface near an audio source. This allowed speech to be identified from micro-vibrations within objects, raising concern regarding the privacy and confidentiality of conversations held within a sound-proof room.

This research has since been continued and tested on robot vacuum cleaners which too incorporate LIDAR sensors intended for spatial mapping. In the application of a robotic vacuum cleaner, light intensity values are considered a side-channel concern as those readings are not required for the operation of a vacuum cleaner. As general off-the-shelf LIDAR sensor units (capable of reading such light intensity values) are used within vacuum cleaners, this technique could be also applied to detect speech and sound (Sriram, Xiang et al. 2020). Despite the limitations of sampling light intensity values on a vacuum cleaner (i.e. accounting for the continuous rotation of the LIDAR sensor and audible noise floor as a result of the vacuum engine), a high classification accuracy of 91% was still achieved when extracting sensitive data from speech such as digits of a credit card.

Whilst this thesis will not pursue the exploration of sensor data analysis, these two studies offer potential future research areas on privacy concerns surrounding robot vacuum cleaners, as newer revisions of smart devices become continually equipped with more accurate and feature-rich sensors.

## Shell access via sideloaded media

Often as a necessary preliminary step to further research, modification and integration of proprietary technologies, many device rooting methods (i.e ways to gain elevated access to a device) have been publicly disclosed on the internet. Commonly, devices which are not expected to have internet connectivity may provide offline firmware upgrade functionality by executing a script or booting from some form of removable flash memory such as a microSD or SD card. Kotlyar (2017) demonstrated the ability for the inexpensive *Xiaomi Dafang Camera* to boot into a custom alternate u-boot bootloader that was flashed onto a microSD card. Upon detection of a firmware-like storage medium, the device executed the contents of the microSD card, and booted into shell instead of the original entry-point script, effectively rooting the device. Kotlyar was then able to dump the firmware, later producing a custom firmware release that did not rely on the vendor’s cloud infrastructure.

Through the subversion of interrupting the default boot sequence, resultant shell access allowed for the development and release of decoupled software. Whilst the exact rooting steps are unlikely to be directly transferable to other devices, the idea of obtaining elevated access via sideloading techniques is an important method to investigate. Throughout the course of the thesis, we attempted to gain shell access via sideloading methods, but were unsuccessful.

## Shell access via BGA pin shorting

For devices that do not automatically boot into removable media, methods have been discovered to force certain SoC’s to enter a recovery or fallback mode. Allwinner-based SoCs implement a mode known as “FEL” that can be entered by pulling a certain pin LOW during boot[[8]](#footnote-9), which allows device manufacturers to perform initial image flashing and bootloader configuration. For developers and hardware hackers, FEL mode allows users to modify the boot environment to execute a shell, allowing for further post-exploitation methods and firmware dumping / analysis.

It is noted that FEL mode can also be entered if the SoC fails to successfully launch the bootloader. Giese (2019) identified this fact and exploited the physical pin layout of the *Allwinner R16* BGA package, where the data pins connecting the SoC to the (e)MMC chips (where the bootloader is stored) were on the physical perimeter of the SoC. By sliding a piece of aluminium foil between the circuit board and the solder plane of the SoC, the electrically conductive aluminium foil could momentarily short the data pins long enough to cause the bootloader read operation to corrupt and fail, hence booting into FEL mode and eventually gaining shell access. This method is favourable when compared to pulling the FEL pin low during boot - as access to the FEL pin would require the desoldering and removal of the SoC from a circuit board - which can be tedious and prone to mistake and irreversible damage.

Through this hardware fault injection technique of shorting data pins during boot, Giese was able to successfully gain access to a shell on Roborock’s first robot vacuum cleaner (*Mi Robot Vacuum Cleaner*). On a different vacuum cleaner (the Roborock S7), Giese noted that test pad TPA17 on the circuit board was connected to the SoC’s FEL pin - allowing FEL mode to be entered by usual means without needing to perform a hardware fault injection.

## Hardware based extraction of flash memory

In situations where no provisions exist to programmatically extract stored data from a system (i.e. shell access to perform disk imaging), hardware devices known as flash programmers can be used; designed to read from and write data onto flash chips. Flash programmers incur a high cost overhead, as they are rather expensive and only work with specific models and/or types of flash chips; rendering it infeasible to own a specific flash programmer for every type of flash chip. Jimenez (2016) points out that a Raspberry Pi could be used as an affordable budget solution when paired with open-source flash programming software like [flashrom](https://www.flashrom.org/Flashrom).

It is noted that the process of hardware flash chip dumping is not feasible in the scope of this thesis due to resource and cost constraints of not possessing a suitable flash programmer, as well as the risk associated with hardware-based methods being possibly destructive with irreversible damage. This method of flash memory extraction was not required as other methods were successfully performed to obtain the firmware data of the device under test.

## Cold-boot attack to dump memory state

Regarding prior investigations of smart robot vacuum cleaners, Ullrich, Classen et al. (2019) performed a security analysis on the Neato BotVac Connected robot. Through the combination of a cold-boot attack - where a system is rebooted without the volatile memory (i.e. RAM) being cleared - and the booting of a custom bootloader image, the memory state of the system’s prior execution was able to be dumped and analysed. This memory dump is of significant value as it would contain the binaries of loaded programs as well as their application state. The proceeding analysis revealed major vulnerabilities and concerns in the vacuum cleaner and more alarmingly, in Neato’s cloud infrastructure.

Whilst logs and coredumps were encrypted when transmitted to cloud servers, encryption keys were discovered to be hardcoded which nullified any assurances of encryption. Authentication and authorisation tokens were all encrypted with the same weak RSA key - which left the entire cloud infrastructure vulnerable to impersonated identities and access. Seemingly random generated keys were also discovered to be vulnerable, due to the keyspace for entropy being so short that the key was able to be bruteforced within reasonable time. Furthermore, an unauthenticated endpoint on the robot vacuum cleaner’s remote port was found to be vulnerable to a buffer overflow, allowing remote code execution on the robot by anyone connected to the same wireless network.

The analysis of a system’s memory state is beneficial to the security assessment of a product’s firmware as static analysis techniques are unable to account for dynamic data such as response payloads from client-server communications. This method of memory extraction was not required as other simpler methods were successfully performed to obtain the firmware data of the device under test.

# Chapter 4 | Threat Modelling

To qualify the observations of proceeding results, it is worthwhile to form threat scenario models, as to identify the different perspectives and their associated risks/concerns that will be assessed.

Table - Threat model matrix

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Threat** | | **TS0** | **TS1** | **TS2** | **TS3** |
| - | Physical (proximal) | Remote (proximal) | Remote (distal) |
| **Concern** | **Physical Access** | **✓** | **✓** |  |  |
| **Remote Access** |  | **✓** | **✓** | **✓** |
| **Data Ownership** | **✓** |  |  |  |
| **Data Visibility** | **✓** | **✓** | **✓** | **✓** |

Table 1 above forms an overview of the four threat scenarios analysed in this thesis.

In *TS0*, we analyse the implications of data visibility and data ownership in a scenario devoid of any malicious threat. This scenario is akin to a product owner who is wary of other parties holding data pertaining to them and wishes to seek transparency in the type and storage of data retained. The scenario additionally extends to a product owner who wishes to maximise the functionality of a device that they purchase and own – such as through improvements or various modifications.

In *TS1*, we assess the threat implications from parties who are within physical proximity of the device. This includes parties as part of the supply chain, second-hand sellers, and individuals who have either momentary, or prolonged physical access to the device. Concerns are raised regarding parties being able to data from the device or regaining control of the device after losing physical access.

In *TS2*, we inspect the ability for a remote party to monitor device communications, or otherwise gain control over a device, without needing physical access to the device at any time. Specifically, the remote party is nearby / within proximity of the device (either within wireless range or connected to a shared computer network).

In *TS3*, we analyse possibility and implications for a remote party to access the device, either through means of a backdoor (possibly planted from *TS1* / *TS2*), or through the vendor’s system themselves. We also assess the ramifications of gaining remote access to an internet-connected sensor-enabled device, however it should be noted that the scope of this thesis excludes the propagation of data in the cloud once received by the vendor.

# Chapter 5 | Work Performed

## Scope and Summary of Work

We begin our work by first defining the scope and extent to which the privacy and security assessment will be performed.

In investigating privacy concerns, we monitor the nature of wireless network activity from a powered off factory-reset Roborock S6 vacuum cleaner when where we pair (initialise), operate, and let the device idle. We observe the device’s behaviour and interaction to other devices on the same wireless network (LAN), as well as its communications to external servers (WAN). This is performed as to better understand the nature of network communications, such as data frequency, duration, size, destination, and content.

In investigating security concerns, we analyse the behaviour and configuration of the system, and identify points of potential compromise or modification that may allow a third-party to gain control of the device, or otherwise render the device insecure. We additionally compare a baseline version of the device firmware to its most recent (April 2022) as to draw insights into how the manufacturer (Roborock) has responded to both the security of the device, and the privacy of the user.

Whilst work and discussions may reference topics from the following: smartphone application communications and interactivity, internal cloud functionality and cloud endpoint vulnerabilities, and the propagation of cloud data - they are beyond the scope of assessment and were performed out of interest, or as aides to other discussion.

Throughout the course of investigation, findings relating privacy and security were not mutually exclusive, and often involved a discussion of both areas. As such, this chapter will be subdivided by work categories, and only briefly overview implications. Detailed privacy and security discussions will follow in the [*Discussions*](#_Chapter_7_|) chapter.

## Preliminary Device Access

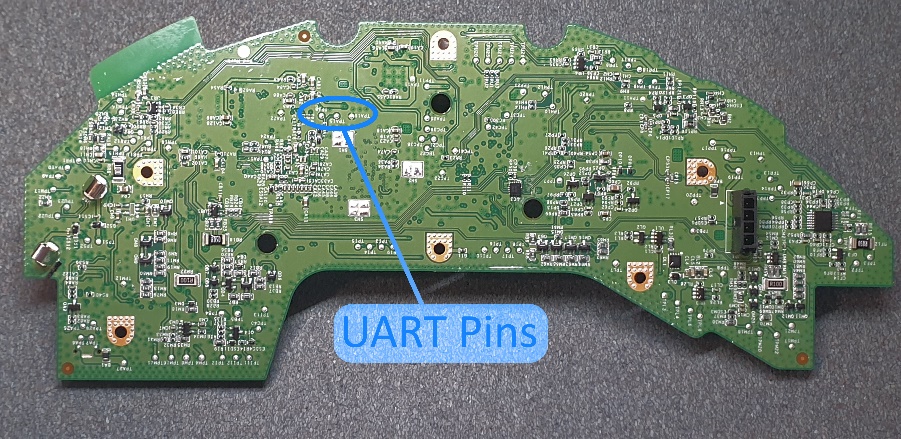


Figure - UART pin locations

As discovered by Giese (2019), the Roborock S6 vacuum cleaner contains circuit board test pads that correspond to the *Allwinner R16* SoC’s configured serial pins, as seen above.  
In detail, TPA8 is the device’s TX pin, TPA15 is the device’s RX pin, and TPA16 is ground.  
A USB to UART adapter can then be used to gain access to the serial interface

Once a serial connection was established (*baud rate = 115200*), functionality in the U-Boot bootloader firmware can be exploited to enter the bootloader’s shell mode, by means of sending multiple ‘s’ characters to interrupt the boot sequence[[9]](#footnote-10). Within the shell, Giese documented a series of instructions to extract the root password from a file called vinda, located inside the device’s eMMC flash. This file contained a 16-byte string, which when XOR’d with the byte 0x37, results in the root password used to gain access to the device. It is noted that root shell access is obtainable without requiring the root password, however it is beneficial.

Table - Root password extraction procedure

|  |  |  |
| --- | --- | --- |
| **Step** | **Command** | **Description** |
| **1** | ext4load mmc 2:6 0 vinda | Load contents of vinda into memory position 0 |
| **2** | md 0 4 | Dump the first 4 words from memory position 0 |
| **3** | ------------------------ | XOR values with 0x37 |

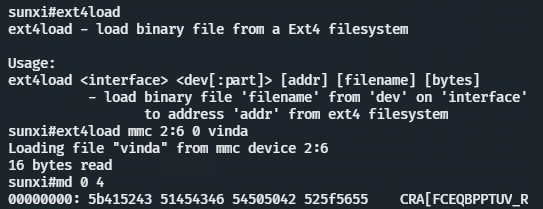


Figure - Password decryption of the vinda file

## Dynamic Firmware Analysis

### Device Fingerprinting

Upon gaining access to the shell, device fingerprinting was performed as to better understand the operating system, hardware feature set and software capability.

It is important to know that the device under test was manufactured in June 2020, one year after the official release of the Roborock S6 vacuum cleaner in June 2019. As a result, the recovery firmware (stored in mmcblk0p7) is versioned 01.15.58 (25th March 2020). All firmware investigation processes and results collected in the proceeding sections were performed against version 01.15.58, until the upgrade analysis section on page 2323.

Table 3 below outlines the various commands and outputs used to identify the system information. Other necessary hardware information (such as storage and memory) is excluded from the table as they are officially listed on the Roborock product webpage[[10]](#footnote-11). Most notably, fingerprint results conclude that the system is running an ARM release of *Ubuntu 14.04.3 LTS*, with *libc* version 2.19 (released 2014). This finding aided the installation and execution of other software that was during the security and privacy assessment of the device under test.

Table - v01.15.58 System Fingerprint

|  |  |
| --- | --- |
| **Command** | **Output** |
| uname -a | Linux rockrobo 3.4.39 #1 SMP PREEMPT Wed Mar 25 20:47:59 CST 2020 armv7l armv7l armv7l GNU/Linux |
| ldd --version ldd | ldd (Ubuntu EGLIBC 2.19-0ubuntu6.6) 2.19 |
| cat /etc/os-release | NAME="Ubuntu" VERSION="14.04.3 LTS, Trusty Tahr" ID=ubuntu ID\_LIKE=debian PRETTY\_NAME="Ubuntu 14.04.3 LTS" VERSION\_ID="14.04" HOME\_URL="http://www.ubuntu.com/" SUPPORT\_URL="http://help.ubuntu.com/" BUG\_REPORT\_URL="http://bugs.launchpad.net/ubuntu/" ROBOROCK\_VERSION=3.5.4\_1558 |
| cat /etc/OS\_VERSION | ro.product.device=MI1558\_TANOS\_MP\_S2020032500REL\_M3.3.0\_RELEASE\_20200325-204847 ro.build.display.id=TANOS\_MP\_R16\_RELEASE\_20200325-204847 ro.sys.cputype=R16.STM32.A3.G1 ro.build.version.release=1558 ro.build.date.utc=1585140527 |

### Process Capability

An instance of htop - a process viewer utility[[11]](#footnote-12) - was loaded on to the device to monitor the running processes as shown in Figure 3, and described in Table 4. Immediate observations revealed that all non-system processes were executed under root-level privileges, which raises device security concerns as a potential vulnerability in any of the executables may lead to system takeover.

It should be noted that it is not uncommon for embedded Linux systems to run processes under the root account during development as difficult IPC and communication port access issues (e.g. udev rules) can be bypassed whilst the product is being developed. If process privileges are not tightened for production or deployment releases however, vulnerabilities are formed regarding least-privilege security principles.

Given the nature of the device running an ARM version of Ubuntu, the execution of foreign binaries was tested successfully, confirming that there no software execution whitelist policies present in the system.

Graphical user interface, text

Description automatically generated

Figure - Process list (v01.15.58)

Table - Important processes (v01.15.58)

|  |  |
| --- | --- |
| **Program** | **Purpose** |
| AppProxy | Central management |
| RoboController | Vacuum cleaner logic |
| rr\_loader | Sensor and cleaning driver |
| WatchDoge | System health and process monitor |
| rrlogd | Device log manager |
| rriot\_tuya | Tuya cloud communications bridge |

### Network Capability

A list of open ports and firewall rules were collected as shown in the figures below. Collected results revealed that ports were exposed on tcp/6668 and tcp/22 (SSH), with the SSH server listening to both IPv4 and IPv6 connections. As suggested in Figure 5, inbound IPv4 connections to the SSH server were dropped, however IPv6 connections were not (Figure 6).  
In effect, efforts to prevent SSH access may have been undermined due to the lack of IPv6 access control restrictions.

To verify this hypothesis, the vacuum cleaner was connected to a wireless network serving DHCPv6 leases from an *Orange Pi R1 Plus* device running [*OpenWRT*](https://openwrt.org/) (as the main network infrastructure did not support IPv6 – see *Test Infrastructure Setup*). Results from ifconfig refuted this theory, as the IPv6 address listed was prefixed with fe80::, which hints that the device did not request for a DHCPv6 lease – hence no IPv6 address was assigned to the device, rending the device unreachable via IPv6.

A screenshot of a computer

Description automatically generated with medium confidence

Figure - netstat (v01.15.58)

|  |  |
| --- | --- |
| Figure - iptables (v01.15.58) | Figure - ip6tables (v01.15.58) |

Text

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Figure - ifconfig (v01.15.58)

### User Enumeration

No novel information was extracted from the /etc/passwd and /etc/shadow files, however it was confirmed that the password hash in the /etc/shadow file matched the root password located in the vinda file, as demonstrated in Figure 10. Upon inspection of /etc/passwd~ file (a backup version of /etc/passwd), existence of a user called ruby was discovered with a home path set to /home/ruby, which existed as a blank directory in the file system - likely being a remnant from a previous firmware version.

|  |  |
| --- | --- |
| Figure - /etc/passwd (v01.15.58) | Graphical user interface, text, website  Description automatically generated  Figure - /etc/shadow (v01.15.58) |
|  |  |

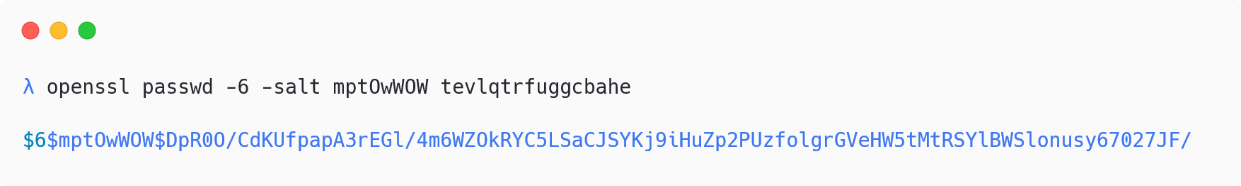


Figure - Generated SHA512 password hash

### Power Analysis

A power analysis was performed to determine how to charge the device’s battery without requiring the charging dock’s charging contacts, as it was difficult to keep the device in contact whilst performing other tests. Figure 11 illustrates the disassembly of the charging dock, which reveals the power leads that connect to the charging contacts. Measurement of the charging terminal voltages whilst loaded and unloaded revealed that dock’s charge controller outputs ~4.2VDC when there is no vacuum connected, and ~20.4VDC when the vacuum is loaded (with an equivalent resistance of 3.7 kΩ)

It was noted that when the 4-wire battery was connected to the device with only the supply leads (+ve and -ve), the device would fail to remain powered on and shutdown after approximately 20 seconds, likely as a fail-safe mechanism as shown in Figure 12.

|  |  |
| --- | --- |
| Figure - Underside of the charging dock | Figure - 2-wire battery shutdown log |

### Data Persistence

Temporary files were created in every directory of the filesystem as to investigate which file paths were untouched during the firmware upgrade, factory reset, and device disassociation (unpair the device via the smartphone application) procedures.

Table - Untouched directories during volatile actions

|  |  |  |
| --- | --- | --- |
| **Firmware Upgrade** | **Factory Reset** | **Disassociation** |
| (mmcblk0p11) /mnt/reserve | (mmcblk0p11) /mnt/reserve | ALL |
| (mmcblk0p1) /mnt/data |  |  |

Where results for upgrade persistence and reset persistence were sensible, the results from device disassociation were alarming, as no data was removed from the device even after the device was deleted from the user’s account. Whilst it could be assumed that device disassociation was then followed by an immediate re-pair process by the same party, failure to follow this flow could potentially lead to PII and UGC being shared to another party if an unpaired device was given away.

Whilst statistical and calibration data (mmcblk0p11) are retained during firmware upgrades and factory resets, it can be noted from Figure 13 that user data (mmcblk0p1) and system partitions are securely wiped (block-writes rather than just files being unlinked in the partition) during the factory reset procedure, preventing data recovery tools like photorec[[12]](#footnote-13) from recovering data.



Figure - Serial log during factory reset

## Static Firmware Analysis

### Firmware Extraction and Layout

To statically analyse the firmware of the device (as to provide a ‘offline’ access to the device’s system), a firmware dump was created with the dd utility via SSH. It is noted that the device had firewall rules in place which needed to be bypassed prior to connecting (as later explained). Following the commands from Figure 14, a set of eMMC partition dumps were created, which have been tabulated as shown in Table 6.



Figure - Firmware dump commands

Table – Firmware partition mapping

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Partition** | **Label** | **Size** | **Mount Point** | **Description** |
| **1** | UDISK | 1.5 GB | /mnt/data | User data |
| **2** | boot-res | 8 MB |  | Bootloader resources |
| **3** | - | 1 KB |  | (unknown) |
| **4** | - | - | - | (does not exist) |
| **5** | env | 16 MB |  | Boot environment |
| **6** | app | 64 MB | /mnt/default | Device data (read only) |
| **7** | recovery | 512 MB |  | Stock firmware |
| **8** | system\_a | 512 MB | / | Firmware A |
| **9** | system\_b | 512 MB | / | Firmware B |
| **10** | download | 528 MB | /mnt/updbuf | Firmware update storage |
| **11** | reserve | 16 MB | /mnt/reserve | Device statistics |

The UDISK partition contains UGC pertaining to map and cleaning data, in addition to device logs and device configurations (such as sound settings, clean scheduling, network settings).

The device contains two copies of the operating system firmware, labelled system\_a and system\_b. If the system fails to boot properly, a hardware watchdog will restart the device, and boot into the other partition. Should both partitions result in a failed boot, or a firmware reset is performed, the contents of the recovery partition (an old stock firmware version) will be flashed onto both system\_a and system\_b. It is noticed that the recovery partition is modifiable.

The reserve partition contains statistical data (officially termed a ‘blackbox’) storing the total number of cleans performed, bumper sensor clicks, hardware information, and error log events. The file structure of this partition is displayed in   
Figure 15 on the following page.

|  |
| --- |
| **mmcblk0p11 (reserve)**  | anonymousid1  | blackbox.db  | CompassBumper.cfg  | counter  | endpoint.bin  | hwinfo  | lds\_calibration.txt  | mcu\_ready  | RoboController.cfg  | rrBkBox.csv  +---rriot  | tuya.json  | try |

Figure – File structure of mmcblk0p11

### Commentree

|  |  |
| --- | --- |
|  | [github.com/featherbear/commentree](https://github.com/featherbear/commentree) |

A documentation tool was created to better mark important regions and annotate lines of plain-text files in the device firmware, which served beneficial in reviewing and analysing text content between research sessions. This tool was used to review and mark the configuration files and logs stored on the device’s filesystem, and additionally provided portability when performing research on different machines. A prototype version is available on [GitHub](https://github.com/featherbear/commentree), with plans to improve and complete it in the future.

Graphical user interface, text

Description automatically generated

Figure - Screenshot of the Commentree tool

### Stock Ubuntu Comparison

As system reconnaissance (see *Device Fingerprinting*) indicated that Ubuntu 14.04.3 LTS was used as the firmware’s base image[[13]](#footnote-14), altered or modified binaries (such as one that has additional features or possible malicious functionality) could be identified through comparing the version in the base image against the device’s version. A byte-level MD5 hash comparison was performed for programs in the /bin, /sbin, /usr/bin, and /usr/sbin directories.

Results concluded that except for one program, all binaries completely matched the base image’s version, which indicates no sign of alteration or modification to existing programs. The binary whose MD5 hash differed[[14]](#footnote-15), ntpdate, is responsible for retrieval and updating of the device’s time from a time server. When performing a function-level binary comparison with BinDiff (as proposed by Costin, Zaddach et al. (2014)), a low similarity ratio of 0.36 was produced as shown in Figure 17 – indicating a large change in program functionality.

Further binary analysis and cross-examination of the assembly call graphs however revealed that the version of ntpdate on the device was only a stripped build of the base version (4.2.6p5@1.2349-o), built without public key cryptography support (provided by *OpenSSL*).

Chart, bubble chart

Description automatically generated

Figure – BinDiff comparison of ntpdate (v01.15.58)

It was also noted that alongside the added vendor software in /opt/rockrobo, the firmware image contained the additional packages rsync, ccrypt, and tcpdump, however rsync and tcpdump had no usage calls in any program (as of version firmware 01.15.58).

Text

Description automatically generated

Figure – apt-get history.log file

### ADB

ADB, short for Android Debugging Bridge, is a development and utility tool to communicate with an Android device, or any device that implements the server functionality. This tool allows for the management and transfer of files, installation of applications (on an Android device), and access to the device’s shell. In the Roborock S6’s firmware there is a custom version of the adbd binary that serves communications (via *FunctionFS*[[15]](#footnote-16)) from the micro USB port located at the top of the vacuum cleaner, as visualised below.



Figure – Exposed micro USB connector on the Roborock S6

The binary has additional functionality to perform system tests (the uart\_test command) and flashing of the device (the ruby\_flash command) without requiring the disassembly of the device to gain access to the programming pins or test pads.

Graphical user interface, text, application, email

Description automatically generated

Figure – Custom adbd auth challenge flow

Access to the ADB interface is restricted however, as a dynamic challenge / response auth process is required to issue adb shell commands. The authentication flow summarised in Figure 20 is as follows:

1. The user requests the challenge token, providing the 16-byte vinda password, followed by ‘rockrobo dynamickey’
2. The user generates the response[[16]](#footnote-17) based off the challenge token and the device’s ID
3. The user issues a command, providing the vinda password string, the response token,   
   and the command they want to execute

If the auth challenge succeeds, further custom access control implementations restrict the commands that can be executed, based off a value of a property named adb\_lock in the read-only /mnt/default/adb.conf file. It is noted that the execution of any arbitrary command is only possible when the value is set to 0, however this is never possible as the adbd binary will reset the value to 1, as shown in the assembly call graph below.

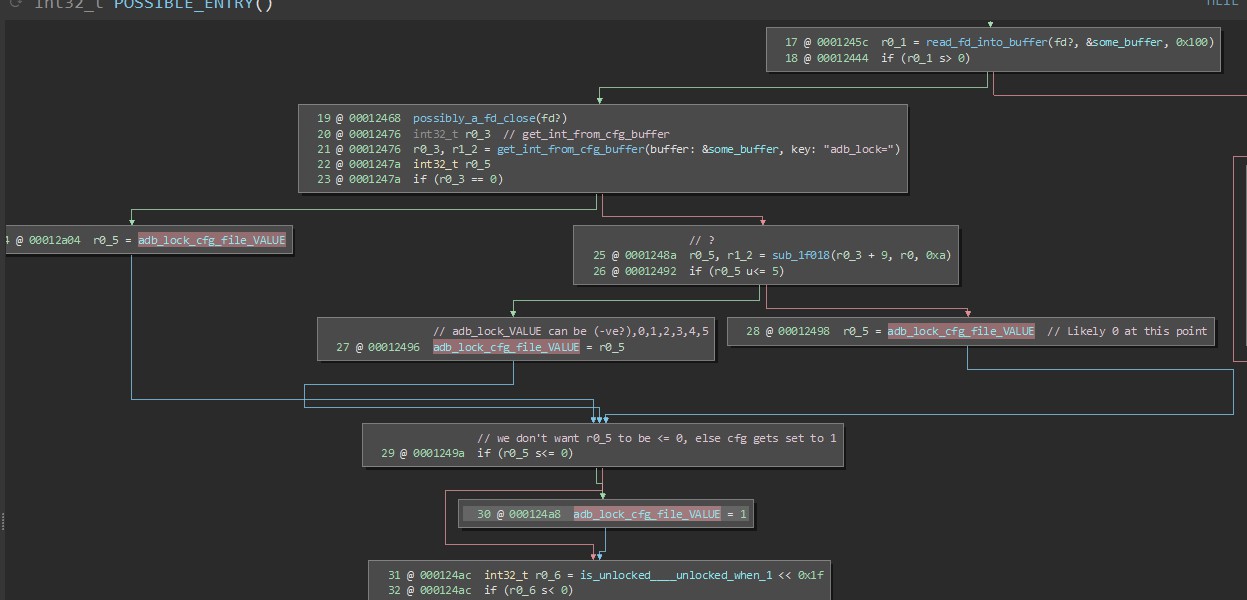


Figure – adbd lock reset flow

A novel command injection vulnerability was discovered in the adbd binary which subverted the access restrictions, allowing any arbitrary command to be executed regardless of the current access level. Whilst the ampersand (&), semicolon (;), pipe (|) and backtick (`) characters are sanitised from the command string to prevent command chaining, failure to filter out the dollar sign ($) character allows for command expansion to be performed via the following command.

adb shell [SYS\_PASSWD][ADB\_PASSWD] uart\_test $(COMMAND)

A proof of concept has been made available[[17]](#footnote-18). This vulnerability additionally exploits the fact that the uart\_test command actually spawns a /bin/sh shell via a *libc* system library function call, which supports command expansions. Arbitrary command execution is obtained, as demonstrated by the proof of concept below. This exploit could be used to exfiltrate data from the system (such as map data and wireless credentials), write to the filesystem, or possibly gain SSH access (as later explained).

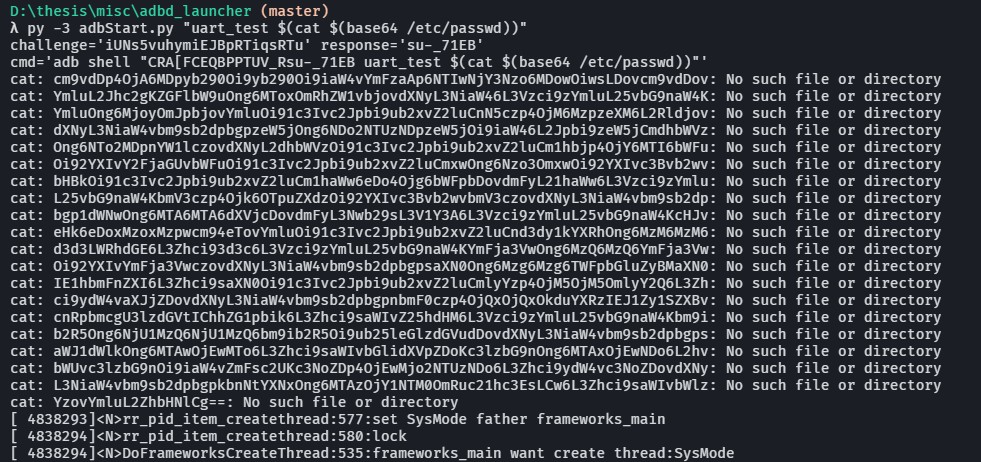


Figure – adbd command injection vulnerability PoC

It is worthwhile to state the limitations of this exploit, as its success relies on the knowledge of the contents of the vinda file, and the device ID. Whilst the device ID is easily obtainable via viewing the USB device information, gaining access to the vinda file is non-trivial, and requires either the disassembly of the device to access the UART pins, or via another exploit.

Nevertheless, whilst this novel exploit does not provide a means to instantly gain control over a device, it provides a post-exploitation method to easily interface with the device over USB, should SSH or serial connections become inaccessible.

### Device Logs (rrlogd)

The rrlogd binary is responsible for the management, rotation and uploading of logs to the Xiaomi File Data Service server[[18]](#footnote-19) (as determined by the device’s manufacture release).

Through both static analysis of the binary, and dynamic analysis of the filesystem, the following categories of log data was observed: application logs relating to vacuum cleaning functionality, application configuration, mapping data[[19]](#footnote-20), firmware upgrade logs, device hardware information, system lifecycle logs, running processes, network information and cleaning statistics. Newer versions of rrlogd (i.e. in the v02.29.02 firmware) also include the ability to upload network captures, as later explained (see *Network Capture*).

Before the logs are upload, they are compressed and encrypted with RSA + AES, as evident in Figure 23. Log files (see Appendix 1) are primarily sourced from the following directories:

* /mnt/data/rockrobo/rrlog/
* /dev/shm/
* /mnt/reserve/

Text

Description automatically generated

Figure - Disassembly of the encryption routine in rrlogd (v01.15.58)

Text

Description automatically generated

Figure – iptables allow rule in rrlogd (v01.15.58)

It was curiously noted that rrlogd implemented functionality to potentially unblock inbound SSH connections depending on the device model. It was however concluded that the specific DUT (Roborock S6) would not satisfy the required conditions and was not affected.

## Upgrade Analysis (Version 02.29.02)

Whilst upgrades are a means to add additional features or improve the performance of existing functions, upgrades additionally assess a company’s response to security vulnerabilities and privacy concerns. It is rather uncommon for vendors to include internal system changes, or detailed security notes in upgrade changelogs as this information will not be of any use to common end-users. Independent research must therefore be performed to produce a system changelog that addresses security and/or privacy concerns.

The DUT was upgraded from v01.15.58 (25th March 2020) to v02.29.02 (28th April 2022), with firmware images being dumped between the incremental upgrades. Static firmware analysis was then performed to compare the changes in the filesystem between versions and has been collated in the table below. In this section of the thesis, the base firmware (v01.15.58) will be compared against the latest version (v02.29.02) to best discern Roborock’s response to security and privacy concerns throughout the product’s life.

Table – Firmware upgrade changelog

|  |  |  |
| --- | --- | --- |
| **Firmware** | **Official Changelog** | **Unofficial System Changelog** |
| **01.17.08 (17th April 2020)** | * Supports multi-floor map saving and robot knows which floor it is * Update to new structured SLAM algorithm to make map more reliable * Support customised room cleaning sequence * Support no-mop zone | * iptables enforcement to drop SSH * rrlogd * WatchDoge * Utilities change to busybox * SSH server changed to dropbear * rriot\_rr added (but not enabled) |
| **01.19.98 (9th June 2020)** | * Improvised Wi-Fi Easy Connect * Overall improvements * Bug fixes * UX fixes | * Serial handler changed to rr\_login |
| **01.20.76 (23rd June 2020)** | * Obstacle avoidance enhancements * Bug fixes and UI optimisation | - |
| **…** | … | … |
| **02.29.02 (28th April 2022)** | * Optimized the quick mapping experience | * rriot\_rr enabled |

### Firmware Images

A security assessment of the firmware upgrade procedure was beyond the scope of this thesis, however it is worthwhile to mention that upgrade packages are encrypted, as observed when intercepted upgrade packages were not trivially extractable. Brief analysis of the SysUpdate binary indicate that packages are additionally signed to prevent unauthorised firmware upgrade files. Whilst a subroutine (as annotated below) indicates that files may be encrypted with ccrypt, this routine is deprecated given that ccrypt is removed in later firmware versions.

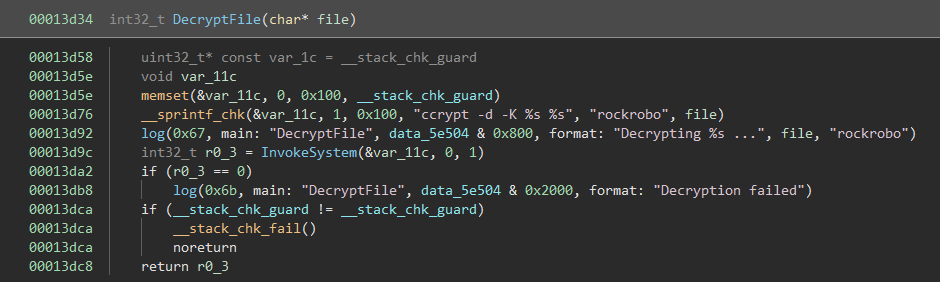


Figure – Obsolete decryption routine in SysUpdate

### Broad System Changes

A filesystem comparison between the base firmware and latest firmware revealed a system migration towards an embedded system design, where functionality is stripped and unused tools are removed from the firmware. In comparison to the base firmware (10680 files totalling 242 MB), a 60% reduction in filesystem size was observed (1976 files totalling 98 MB).

Most noticeably, many utilities were replaced with a busybox distribution (v1.24.1), commonly used in embedded Linux systems as a means to decrease firmware image size. Ubuntu-like and Debian-like files and folder structures (including the apt-get and dpkg package managers) were additionally removed in later firmware versions. Whilst the removal of package managers does not prevent foreign binaries from being loaded and executed, it does significantly increase the time required to execute foreign binaries.

It was also noted that the rsync and ccrypt binaries previously found in base firmware were removed, however the added tcpdump package remained.

MD5 hashes were calculated for the binaries in the latest firmware and were compared against the base firmware (see *Stock Ubuntu Comparison*) to determine if files were changed. All shared binaries (ignoring programs replaced with busybox) in the /bin, /sbin and /usr/sbin directories matched, indicating that no changes exist. Whilst some binaries in the /usr/bin directory were modified, functional analysis comparisons concluded that only performance changes were made.

We now outline the non-trivial changes noticed between the base firmware and latest firmware.

### IPv6 Routing

As previously assessed during the dynamic firmware analysis of the Roborock S6 (see *Network Capability*), no ip6tables rules were applied in the base firmware – however as the device did not request nor assign itself an IPv6 address (other than its link-local address), access to exposed ports on the device via IPv6 were denied. Despite the device being unreachable via IPv6, newer firmware versions explicitly prevent IPv6 traffic (in both directions) by enforcing DROP rules to all network chains, as shown in the program output below.

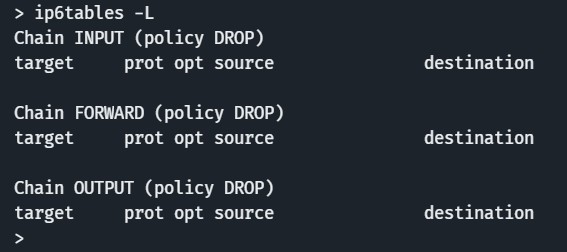


Figure – ip6tables results (v02.29.02)

### Authentication Flow Modification

In the base firmware, device authentication from a terminal interface (such as through SSH or serial) was managed through the standard pam\_unix.so module, which would utilise the authentication information within the /etc/passwd and /etc/shadow files. It was noted that the root password was identical to the decrypted value of the vinda file contents in the device data partition (see *Firmware Extraction and Layout*).

Newer firmware versions (as of firmware version 01.19.98, released 9th June 2020) however no longer use the standard module to authenticate login requests, and instead use a custom authentication routine called verify\_shadow located in the vendor’s libuart\_api.so library. As visible in the disassembly below, the presence of a /mnt/default/shadow file is noted – whose purpose likely mirrors the /etc/shadow file (to store password hashes). The presence of /mnt/default/shadow.sign is also noted, used in an RSA signature check to verify the integrity of /mnt/default/shadow. It is inferred that modification to the root password is difficult without knowledge of the RSA key used to perform the signature signing.

This authentication flow modification does not apply to all authentication interfaces on the system, as the /bin/login and su binaries still utilise the standard Unix authentication. Only programs which specifically use the libuart\_api.so library (i.e. vendor software) are affected by this authentication flow modification.

Text

Description automatically generated

Figure – verify\_shadow function routine

The DUT specifically used during this thesis however did not contain the shadow or shadow.sign file, likely due to the authentication flow changes not yet propagating through the manufacture and initial device flashing process. Consequently all authentication methods in firmware versions which utilised the verify\_shadow routine (serial, SSH, ADB) would always fail, as the missing files would trigger early exit conditions.

It is noted that the manufacture date (June 2020) of the Roborock S6 vacuum cleaner specifically used during the thesis was unideal, as it coincides with the release month of firmware version 01.19.98, where this authentication flow modification was implemented. This raises uncertainty regarding how the vendor may have modified the filesystem. As the base firmware was versioned in March, it is assumed that the DUT has the filesystem structure of a device manufactured prior to June, and hence prior to the authentication flow modification.

It would be possible to patch the libuart\_api.so binary to always return a successful verification result, however this was not tested as it would require greater effort as compared to other trivial methods to gain access.

### Serial Access

Later firmware versions replaced the original serial handler /sbin/getty with a custom implementation named rr\_login. Similar to the patched SSH interface, this binary restricted serial access (see Appendix 2) to only the root user, and utilised the verify\_shadow authentication flow - which would always fail with the DUT.

As consequence to the serial login always failing because of the missing shadow and shadow.sign files, the following steps were developed to regain access to the console by replacing the serial handler in the /etc/inittab file (see Figure 28).

|  |
| --- |
| * + 1. Boot into the u-boot debug shell by sending ‘s’     2. Overwrite the init entry point to start /bin/bash        - setenv setargs\_mmc ${setargs\_mmc} init=/bin/bash     3. Resume system boot with the boot command     4. Disable the hardware watchdog        - echo V > /dev/watchdog     5. Edit the /etc/inittab file        - Remove ::respawn:/sbin/rr\_login -d /dev/ttyS0 -b 115200 -p vt100        - Append ttyS0::respawn:/bin/login     6. Reboot the system with the reboot command |



Figure – SysV configuration script (v02.29.02)

Upon modification of /etc/inittab, serial access was restored allowing access to the device with the original root password.

### SSH Access

In the base firmware, a stock *OpenSSH* server was exposed on tcp/22 on both IPv4 and IPv6 addresses (albeit no IPv6 connection was able to be established), the upgraded firmware revealed that the SSH server was replaced with dropbear (v2013.60), a compact SSH server that is commonly used in embedded Linux system. Notably, this dropbear binary was modified to limit access solely to the root user and implemented the aforementioned verify\_shadow authentication flow. The standard Unix authentication flow can be restored by replacing the dropbear binary with a stock or alternate server binary.

It was also noted that the dropbear binary only offers two legacy key exchange algorithms, diffie-hellman-group1-sha1 and diffie-hellman-group14-sha1, both which are considered to be weak by modern cryptography standards and may be vulnerable to the attacks like *Logjam (Adrian, Bhargavan et al. 2015).*

A binary analysis of the WatchDoge and rrlogd binaries in the latest firmware reveal that extra functionality was implemented to further enforce SSH access restrictions (as previously established in the *Network Capability* section), as evident in Figure 29, where the very first functional instruction was to call iptables -I INPUT -j DROP -p tcp --dport 22.

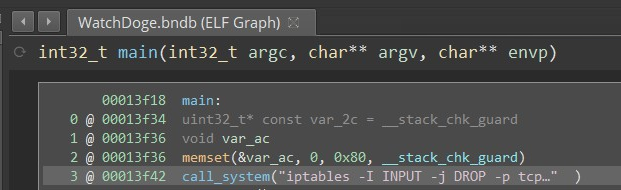


Figure – WatchDoge process enforcing iptables

### Network Capture

Static analysis of the updated rrlogd binary in the latest firmware revealed new IPC signal handling behaviour. When the MSG\_LOG\_DEBUG\_ENABLE signal was received, a function in the wlanmgr process is called, whose behaviour is as described below.

Table – wlanmgr routine 0x136e8 (v02.29.02)

|  |  |  |
| --- | --- | --- |
| **Signal** | **Action** | **Description** |
| **0** | rm -rf /mnt/data/debug | Delete debug files |
| **1** | tcpdump -i any -s 0 -C %lu -W %d -Z root -w %s/%s/%s & | Perform packet capture |
| **2** | killall tcpdump | Stop packet capture |
| **3** | /opt/rockrobo/wlan/ wifi\_debug\_collect.sh | Collect other network information |

Most notably, the wlanmgr process was observed to be able to create network packet captures via tcpdump. When rrlogd receives the MSG\_LOG\_DEBUG\_UPLOAD\_DATA signal, the packet capture dump along with other files (as referenced by the wlan\_debug\_collect.sh script) are uploaded to the log servers. The table below details the content of uploaded data.

Table – Collected network data (v02.29.02)

|  |  |  |
| --- | --- | --- |
| **Filename** | **Source** | **Description** |
| resolv.conf | /etc/resolv.conf | DNS nameserver configuration |
| netstat.txt | netstat -anp | List of all sockets and related processes |
| ifconfig.txt | ifconfig | Overview of network interfaces |
| network\_packet.pcap | (wlanmgr) | Packet captures |

As the network packet capture is performed using tcpdump, only TCP packets are captured within the dump file, and does not include any UDP traffic. It should also be noted that the visibility of network traffic is limited to the traffic broadcasted by the access point, as only a passive network capture is performed.

## Network Activity Analysis

This section covers the security and privacy assessments pertaining to network traffic and device communications. Network packet captures were performed during the research period, capturing network activity during the following scenarios and events:

* Device is uninitialised – Perform pairing and initial setup
* Device is initialised – Perform cleaning
* Device is initialised – Perform firmware upgrade
* Device is initialised – Device idle

### Test Infrastructure Setup

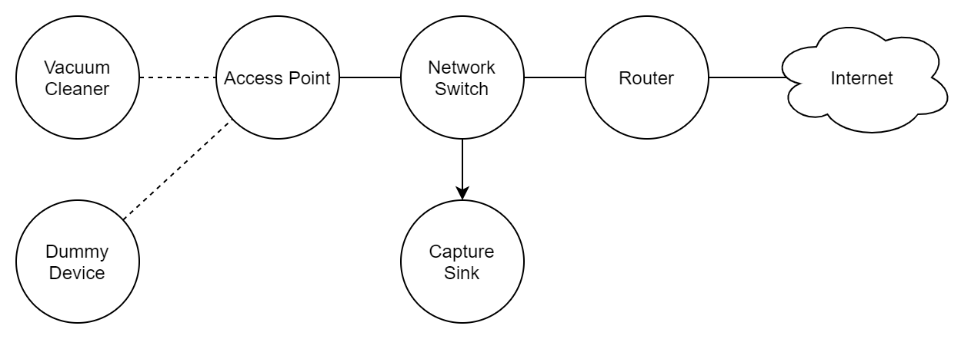


Figure - Isolated network connection diagram

Table - Network equipment list

|  |  |  |
| --- | --- | --- |
| **Label** | **Device** | **Purpose** |
| Vacuum Cleaner | Roborock S6 | (Device Under Test) |
| Dummy Device | Lenovo M93p Tiny | Simulate network traffic |
| Access Point | Ubiquiti UniFi UAP | Provide Wi-Fi connectivity |
| Network Switch | TP-Link TL-SG105E | Network expansion, port mirror |
| Capture Sink | Mac Mini | Port mirror |
| Router | Routerboard RB1200 | Network gateway |

An isolated network (disconnected from personal devices) was set up to securely monitor the network traffic of the vacuum cleaner without external influences. The Roborock S6 vacuum cleaner was connected to a WPA2-PSK secured wireless network (via the access point), and network activity was *port-mirrored* to a capture sink for packet capturing purposes.

*Port-mirroring* is a network observability function to copy network traffic flowing through a switched port to another port, often to allow for the transparent monitoring of data without requiring a physical network tap. Given the nature of network switches only forwarding data to the required destination port (compared to a network hub which broadcasts data to all connected ports/clients), port mirroring allows for the traffic of the wireless access point (and consequently the vacuum cleaner) to be monitored. As access points function as network hubs, the port-mirroring of the access point effectively provides a means to view all the packets that the vacuum cleaner itself can see.

Due to the port mirroring functionality limitations specific to the network switch used during this thesis (*TP-Link TL-SG105E*), modifications to the capture sink’s NIC required to only permit unidirectional data transmission from the switch to the capture sink, as to effectively disconnect the capture sink from the network whilst still receiving port mirrored traffic.

As the device may exhibit different behaviour under a sterile environment (no other devices connected that produce network activity), a “dummy device” was connected to the same wireless network to simulate common traffic with the nping utility.

Packet captures were performed in several batches over several months under the previously mentioned test scenarios, with most captures being performed whilst the device was idle - as it would best reveal any network activity patterns. Packet captures were performed on both firmware versions 01.15.58 and 02.29.02.

### Data Transparency Preparation

Given the encrypted nature of network communications present on the device, steps must be taken to decrypt or otherwise transparently observe the encapsulated payload or message. Before exploring the actions taken in this thesis to meaningfully observe the network traffic, we first overview common issues faced by developers and other security professionals when dealing with analysis of encrypted network traffic.

Table – Comparison of data transparency methods

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | SSLKEY LOGFILE | MITM (e.g. Burp Suite) | Frida | Manual Patching |
| (Straight-forward) System-level configuration possible | **✓** | **✓** |  |  |
| Always respected by application |  |  | **✓** | **✓** |
| Non-HTTP TCP traffic support |  | **✓** | **✓** | **✓** |
| UDP traffic support |  |  | **✓** | **✓** |
| Application-level crypto support |  |  | **✓** | **✓** |
| Requires access to the binary |  |  | **✓** | **✓** |
| Difficulty | Easy | Medium | Hard | Even Harder |

Certain programs and web browser such as Firefox and Chrome implement a development feature where SSL / TLS session secrets can be stored in a file (via the SSLKEYLOGFILE environment variable[[20]](#footnote-21)). This file can then be used to aid packet capture analysis tools such as Wireshark to decrypt encrypted SSL / TLS sessions, and consequently view the unencrypted payloads. Whilst seemingly useful, this method is not protocol agnostic and can only be used to decrypt website traffic.

Embedded systems such as the Roborock S6 may include software that do not communicate over HTTP(S) – in fact this is often the case as the adoption of MQTT or custom protocols are becoming more prevalent in IoT systems (Mishra and Kertesz 2020). There is also no guarantee that all applications will respect the presence of the SSLKEYLOGFILE variable.

As observed during the static firmware analysis, binaries of the DUT implement application-level encryption, and hence do not rely on SSL / TLS encryption to secure communications. Even if SSL / TLS encryption could be stripped, this method does not provide any means to decrypt application-level encryption. This limitation also exists in MITM solutions such as [*Burp Suite*](https://portswigger.net/burp), [*mitmproxy*](https://mitmproxy.org/) and other associated utilities[[21]](#footnote-22) that only aid in SSL / TLS decryption.

Dynamic instrumentation frameworks like *Frida*[[22]](#footnote-23) exist to solve the inability to decrypt application-level encryption, by instead hooking into the program’s function calls. Through function hooking, unencrypted payloads can be obtained by intercepting the pre-encryption and post-decryption stages. The utilisation of Frida was not pursued due during the thesis due to initial technical issues and time constraints.

The modifiable nature of binary files in the filesystem instead allowed for the injection of crafted ARM assembly code that relayed the pre-encrypted / post-decrypted payloads over the network to an arbitrarily defined address *10.251.252.253:28422 (UDP),* as seen in the figure below. By transmitting the payload data over the network, payloads were also captured in the packet capture, which consequently simplified the process of correlating network traffic.



Figure - Crypto function hook source code

It was also noted that certain encrypted traffic (such as the upload of log data) could be studied by simply viewing the underlying log files within the filesystem.

### Overview of Network Endpoints

The table below summarises the endpoints that the Roborock S6 vacuum cleaner connects to and is provided to give context to the upcoming observations and results.

Table – Overview of network endpoints

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Endpoint** | **Protocol** | **Description** | **Used in 01.15.58** | **Used in 02.29.02** |
| ms.tuyaeu.com | MQTT | Inbound requests |  | **✓** |
| m2.tuyaeu.com | MQTT | Inbound requests | **✓** |  |
| a2.tuyaeu.com | HTTPS | Outbound requests | **✓** | **✓** |
| awsde0.fds.api.xiaomi.com | FDS[[23]](#footnote-24) | Logs upload | **✓** | **✓** |
| xx.ot.io.mi.com | HTTP | (unknown) | **✓** |  |
| xx.ott.io.mi.com | HTTP | (unknown) | **✓** |  |

Figure 32 below visualises the nature of dataflows between the device and external endpoints and displays the inter-process communication flow between relevant processes on the device.

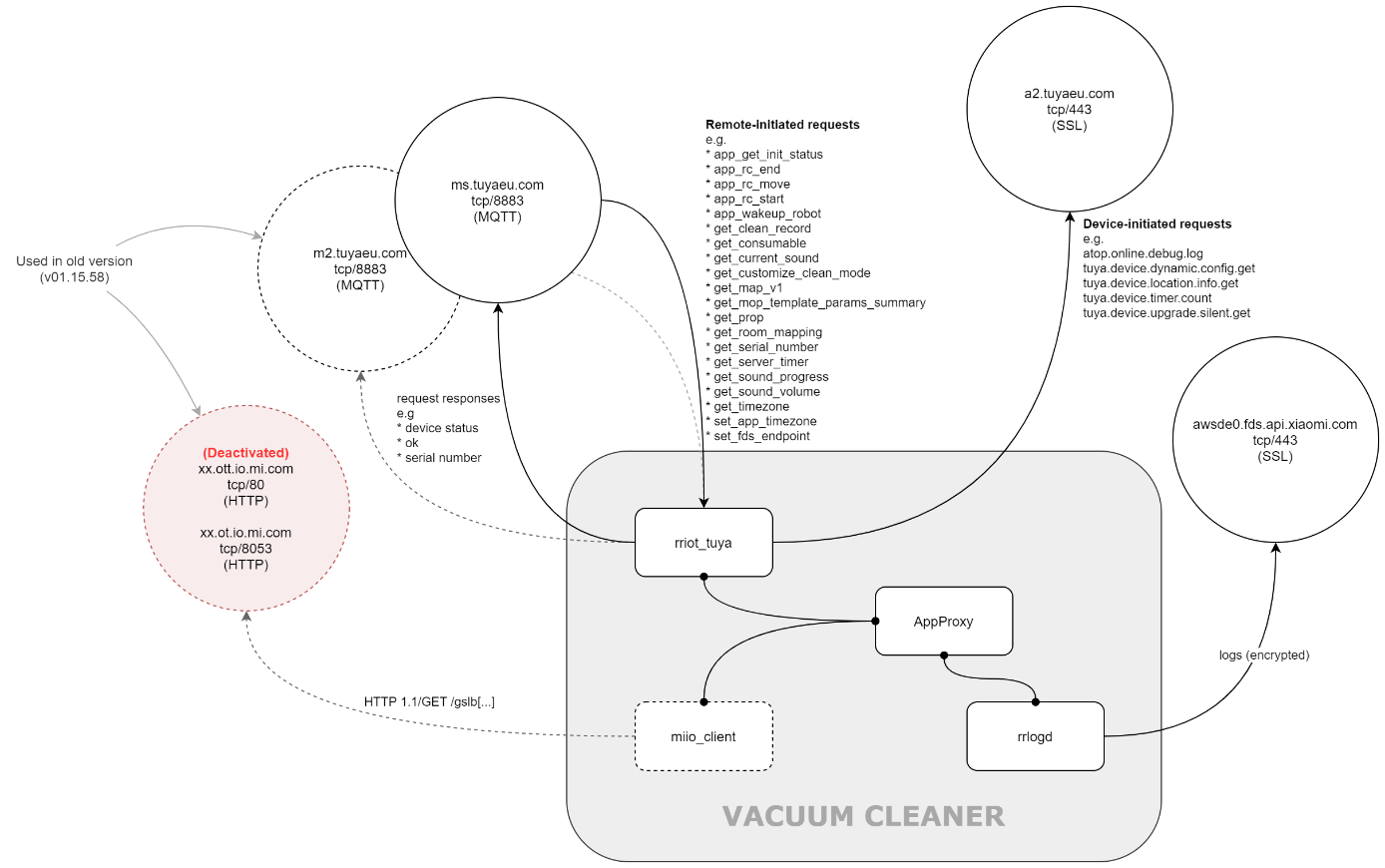


Figure – Network communication diagram

### Network Content Analysis

#### Exploration

The MQTT servers (m2.tuyaeu.com, ms.tuyaeu.com) are responsible for the requests sent by the server to the device, such as status checks and queries for device settings. Commands sent by the smartphone companion application to remotely navigate the Roborock S6 are also delivered through the MQTT protocol (as labelled by the app\_rc\_move request). Payloads are packed as JSON for both requests and replies.

The a2.tuyaeu.com endpoint is responsible for requests initiated by the device and set to the server. These requests include firmware update checks and configuration update polls and are also packed in the JSON format.

As previously mentioned in the static analysis of the Device Logs (rrlogd binary and further explored during its [upgrade analysis](#_rrlogd), logs are compressed and secured with RSA + AES before being uploaded to the Xiaomi FDS server (awsde0.fds.api.xiaomi.com). These logs included application config and runtime data, device data, system lifecycle data, cleaning statistics and network capture data (as seen in v02.29.02).

In version 01.15.58 of the device firmware, HTTP GET requests were issued to the xx.ot.io.mi.com and xx.ott.io.mi.com endpoints, however these endpoints appear to be deactivated as they produced no meaningful response (HTTP Error 400).

#### Privacy Policy Violation

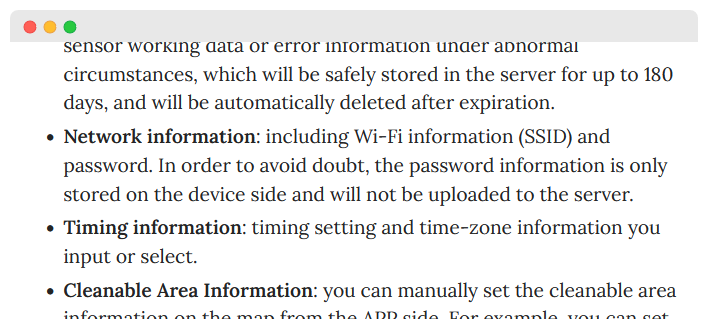


Figure – Privacy policy excerpt

As shown in Figure 33, the privacy policy (effective 30th April 2019) for vacuum cleaner data in the Android version of Roborock’s smartphone application (app version 3.2.48) states that the “password […] is only stored on the device” – however the screenshot below showing contents of the uploaded rriot\_tuya.log file contradict the statement. Despite firmware version 02.29.02 being released 28th April 2022, the wireless network name and password are clearly visible within the log file.

It was noted that whilst a newer dated privacy policy (12th November 2021) was found on the vendor’s website[[24]](#footnote-25), the privacy policy scope only addressed ‘Email Subscriptions’ and not of the privacy of data on, or of the vacuum cleaner.

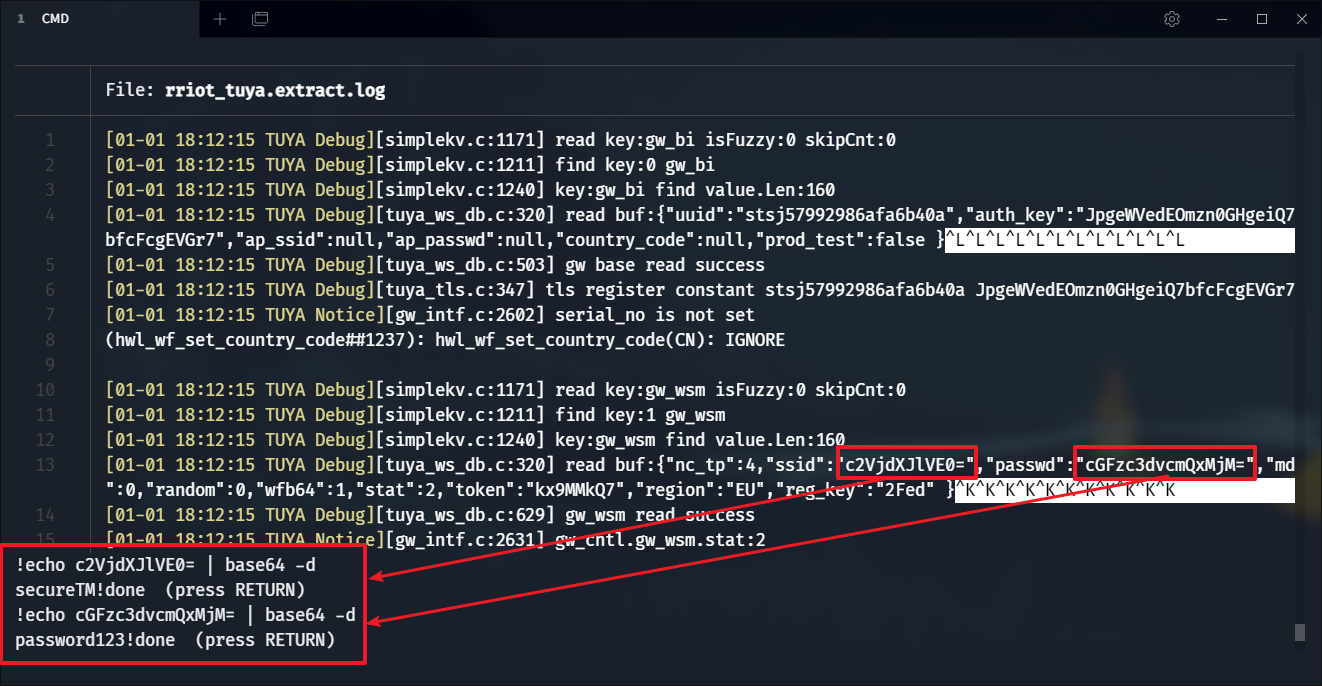


Figure – Exposure of wireless credentials in rriot\_tuya.log  
(FW: v02.29.02)

#### Pairing Traffic

When the Roborock S6 is uninitialised / factory-reset, the device enters Access Point mode, and broadcasts an SSID named roborock-vacuum-s6\_miapXXXX, where XXXX is replaced with the last four characters of the device’s MAC address. The companion smartphone app will then connect to this access point and send the configuration frames to continue the pairing process. It was noted that the network was not secured with any passphrase, and consequently has no WEP / WPA security protecting transmissions. External parties can easily monitor the traffic of open networks, even without needing to join the network (given possession of a wireless adapter that supports promiscuous monitoring).

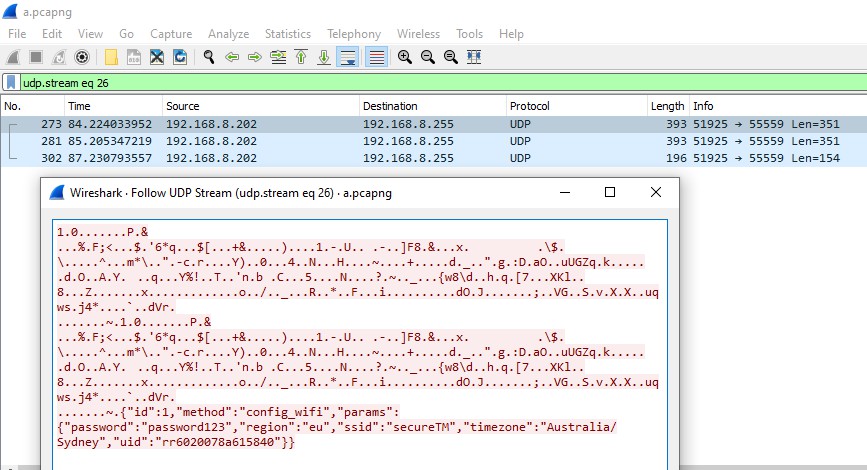


Figure - Plain-text credential transmission during pairing

Network activity captured during the device pairing action revealed that the JSON-encoded configuration payload (containing the wireless credentials) was transmitted from the smartphone application to the robot over plain-text, as visible in Figure 35. Here, the SSID secureTM, and password password123 are visible to anyone monitoring the network traffic. This observation of the plain-text transmission of wireless credentials violates the IoT ecosystem’s official security guidelines (Tuya Smart 2020), which outline the requirement for a product to “use AES encryption to transmit […] Wi-Fi information”, and is synonymous with previous security and privacy studies on devices using the Tuya IoT ecosystem (Vtrust 2018).

### Network Behaviour Analysis

#### Local Traffic

A high number of local traffic requests was observed being emitted by the DUT, albeit small in volume (< 3MB). The following local network behaviour was observed:

* Every 5 minutes a DHCP lease request was issued by the device
* Every 5 seconds the rriot\_tuya process issued a *Tuya Discovery Packet*
  + Broadcast to udp/6667 containing the device identifier and IP address

Specifically for firmware v01.15.58, the following additional behaviour was observed:

* Every 5 minutes an SSDP poll was issued by the device
  + This is an artifact of the operating system effectively running Ubuntu
* Every 10 seconds the miio\_client process issued a request to xx.ott.io.mi.com
* Every second the miio\_client process issued 2 requests to xx.ot.io.mi.com

#### External Traffic

The following traffic reports are based off network captures whilst the device was not in operation (idle) to determine network behaviour patterns. External traffic is broken down by endpoint to better characterise each individual process, and further broken down into hourly segments with times labelled in reference to Australian Eastern Standard Time (GMT+10).

##### Inbound Requests (ms.tuyaeu.com / m2.tuyaeu.com)

|  |  |
| --- | --- |
| Figure – MQTT server data heatmap | Chart  Description automatically generated with medium confidence  Figure – MQTT server historical overview |

The network heatmap above indicates increased network activity around 3am every day, however during these peaks, at most, only 300 KB of data was transferred. Application logs from rriot\_tuya reveal that the increased activity is a result of the program timing out and reconnecting daily at 3am. A small packet was transmitted every minute; however, it was determined to be an MQTT keep-alive packet.

##### Outbound Requests (a2.tuyaeu.com)

Graphical user interface

Description automatically generated with medium confidence

Figure – Control server data heatmap

The rriot\_tuya process exhibits more behaviour when communicating to the control server, evident in the increased dataflow counts in the figure above. Whilst increased dataflow is observed, total average hourly bandwidth does not exceed 10 KB, with peak hourly consumption of 20 KB at 3am every day. It was observed that a tuya.device.timer.count request was emitted every 25 minutes likely as an uptime poll, which aids in explaining the above heatmap. When the device reconnects to the MQTT server at 3am, upgrade checks and configuration polls are emitted, explaining the coincident activity.

##### Logs (awsde0.fds.api.xiaomi.com)

|  |  |
| --- | --- |
| Figure – FDS server data heatmap | Chart  Description automatically generated with low confidence  Figure – FDS server flow graph |

Inspection of the rrlogd process revealed that it did not transmit nor receive data from the FDS server unless logs were being uploaded. The behaviour of somewhat regular network activity (as visible in the 2022-07-06 to 2022-07-11 timeframe) can be attributed to the log sizes growing and reaching the threshold limit which triggers the logs to be uploaded. Likewise, when the MQTT connection is re-established, the increased log activity triggers logs to be uploaded, hence why all services incur increased activity at 3am. It was noted that the FDS servers which the device uploaded logs to were situated in Germany and the United States as visualised in Figure 41 below.

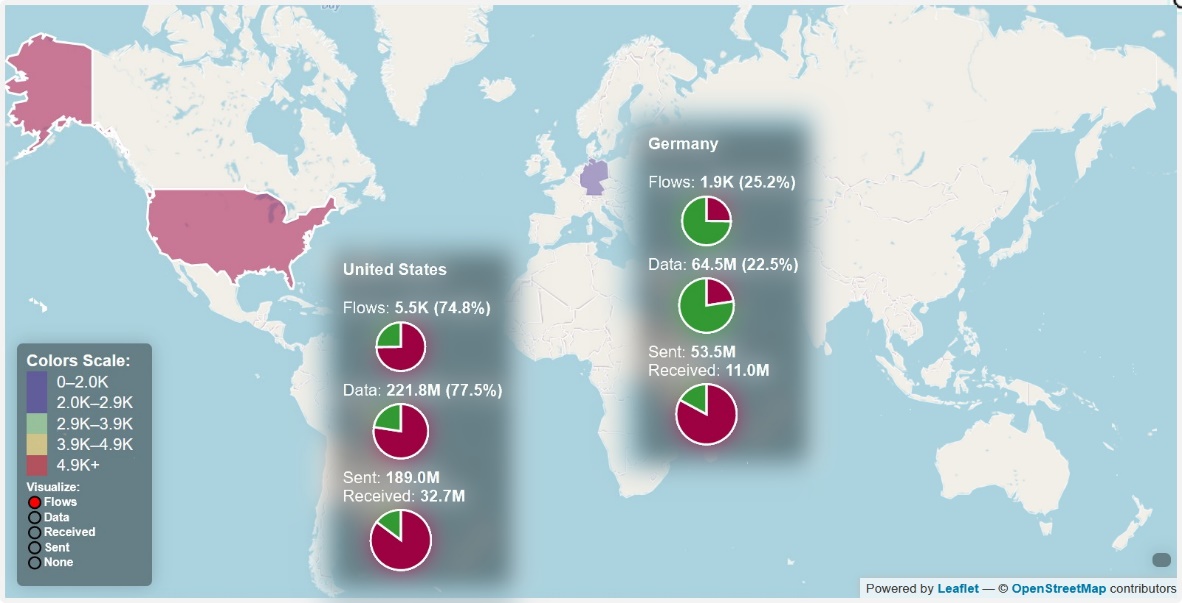


Figure – Geomap of device activity to Xiaomi FDS servers

#### Device Docking

It was noted that network activity (both flow count and traffic volume) would increase when the vacuum returned to the charging dock after cleaning, or when manually docked. This was in accordance with a configuration parameter ONLY\_UPLOAD\_ONDOCK=1 found in the rrlog.conf file.

### Manufacturer Usage Description (RFC 8520)

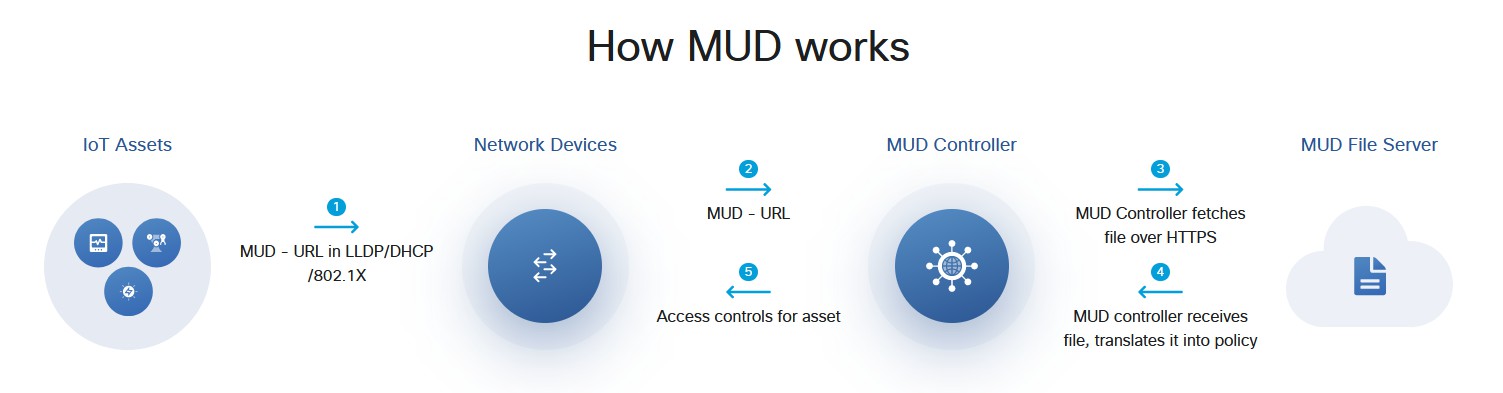


Figure – MUD usage diagram

Drafted in 2016, and published in 2019, the Manufacturer Usage Description (MUD) specification provided mechanisms for a networked device to advertise its expected network activity and behaviour. The supporting network infrastructure can then make use of this MUD profile (as outlined in Figure 42) to determine whether certain network traffic should be blocked or allowed at the switching level. For example – traffic emitted by a device to example.com:8890/tcp can be dropped if the device’s MUD profile does not contain a definition for traffic flow to example.com via tcp/8890 – which can potentially mitigate foreign processes on a device from reaching out to the internet.

Whilst communication to distinct ports and hostnames can be controlled via RFC8520, there is no ability to perform deep packet inspection – payloads sharing the same connection cannot be differentiated. Consequently, this protocol can only be used to protect foreign and unidentified traffic connections and should not be relied upon to protect a network or device from all network threats (such as vendor C2, MITM and spoofing attempts).

As Roborock has not released MUD profiles for the Roborock S6, a set has been created (Hamza, Ranathunga et al. 2018) from the network traffic captured from firmware versions 01.15.58 and 02.29.02; and is publicly offered[[25]](#footnote-26) to promote the adoption of RFC8520.  
An excerpt of the generated MUD profile is provided in Figure 43.



Figure – MUD profile snippet (v02.29.02)

## Device Entry and Persistence Analysis

We now detail methods to grant local access to, remote access to, or otherwise root the Roborock S6 vacuum cleaner to provide additional functionality and or capability. This section covers the practical methods and building blocks that a malicious actor may use, however discussions regarding security and privacy implications will be held until the chapter on [Discussion](#_Chapter_6_|)s.

Table 13 below is provided to summarise the proceeding content.

Table – Overview of device entry and access methods

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Serial (UART)** | **USB (ADB)** | **SSH** | **MiIO OTA** | **Backdoor** |
| **Requires vinda** |  | **✓** |  |  |  |
| **Requires Modifications** |  |  | **✓** |  | **✓** |
| **Requires Physical Access** | **✓** | **✓** |  |  |  |
| **Fortified**✝ | **✓** | **✓** | **✓** | **✓** |  |
| **Upgrade Resistant**# |  | **✓** |  |  |  |

✝Fortified: as describing if the vendor has implemented changes over the lifetime of the product to prevent or otherwise restrict access

#Upgrade resistant: as describing if an entry method will continue to work immediately after an upgrade is performed

### Device Entry

#### Serial (UART)

The device’s serial console (see *Preliminary Device Access*) is likely the first point of entry to gain remote access. This method however requires physical access and disassembly of the device, as the UART pins are located on the device’s circuit board located within the device. Familiarity and the confidence to touch electrical circuits are also required, in addition to the possession a serial device interface (i.e. a USB to UART adapter).

In newer firmware versions where rr\_login is used as the serial handler, additional work must be performed to gain root access, due to the verify\_shadow authentication flow. After the initial connection however, the serial handler can be modified to use the old /bin/login handler, which utilises the old Unix authentication method.

#### USB (ADB)

As mentioned previously (see *ADB*), access to the device via the ADB port is restricted due a custom authentication challenge, and further access restrictions even after authentication. Where the proposed novel exploit can be performed to remotely execute commands, an alternate method exists where the custom adbd is simply replaced with a fully functional version, bypassing all added authentication stages. The exploit method however remains resilient to upgrades (until patched by the vendor).

Whilst access to the ADB port is simple and quick (the micro USB port is located underneath the removable lid of the device, both methods (command injection, binary replacement) require prior access to the device – to either gain knowledge of the vinda content, or to access a shell.

#### SSH

In legacy firmware versions, the rrwatchdoge.conf configuration file could be modified to nullify the offendin iptables command, as shown in Figure 44. However, in newer firmware versions where the modified dropbear SSH server is used, the iptables drop command is present in multiple locations (S04wdgenv, WatchDoge, rrwatchdoge.conf, rrlogd) and consequently each file must be patched to permit SSH access. In patching the WatchDoge and rrlogd binaries, calls can be simply nullified by replacing the instructions with NOP instructions, or by replacing the string ‘22’ with a spurious value like ‘27’, as to cause the wrong TCP port to be blocked, whilst maintaining similarity in the assembly code execution.

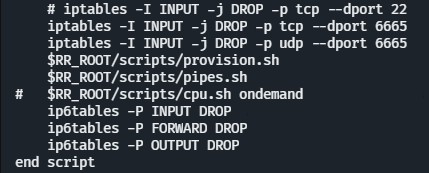


Figure – rrwatchdoge.conf with SSH access patch

Access to the SSH server is heavily reliant on the ability to manipulate the filesystem, and hence requires prior access to the device. It is beneficial to replace the dropbear binary with an *OpenSSH* server implementation, to allow non-root user authentication whilst supporting more secure key exchange algorithms (see *SSH Access*) and possibly supporting file transfers via SFTP. It is also worthwhile to create an additional user on the device, as to provide an alternate backup login account.

#### MiIO OTA

Prior to November 2019, Roborock S6 devices supported over-the-air firmware upgrades via the MiIO protocol[[26]](#footnote-27), where a packet could be transmitted to the device containing instructions to upgrade the firmware, as visualised in Figure 45. The device would then fetch the firmware and execute the associated setup scripts. The ability to control the firmware URL to a user-provided package provided the potential to remotely root, or otherwise gain control over the device without requiring physical access and/or the disassembly of the device.

The MiIO OTA rooting method has limited use as only devices manufactured within four months of the product’s release (June 2019) were supported. Consequently, this method was not applicable to the DUT, as it was manufactured after the method was disabled, however a downgrade of the miio\_client and SysUpdate binaries confirmed the past exploitability of this method (using miio\_client version 3.3.9). Figure 46 visualises the assembly code graph of miio\_client version 3.5.4, where modifications were made to discard the miIO.ota payload and cause the process to follow the silent fail path in red.



Figure – MiIO OTA payload

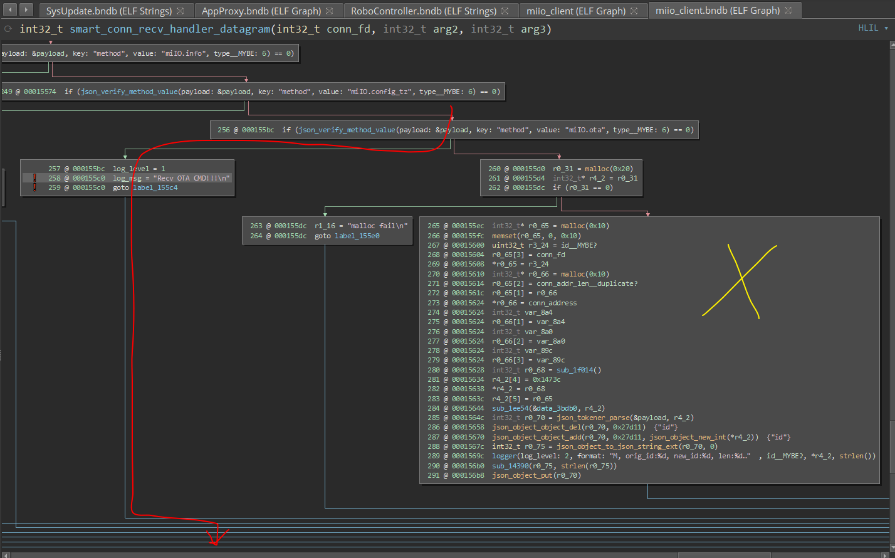


Figure – Silent fail of the miIO.ota payload

### Persistence

#### Remote Access Persistence (Backdoor)

In benefit of the device’s network stack capability, a virtual private network (VPN) utility or software defined network (SDN) tool such as *ZeroTier[[27]](#footnote-28)* can be installed, allowing remote communication with the device through standard IP networking, gaining access to local device services such as SSH. A proof of concept has been made available[[28]](#footnote-29).

Other remote access methods such as a reverse shell can also be established given the freedom of software and hardware support. Figure 47 below provides insights into the ability to create private ad-hoc networks despite a remote network topology.

It is worthwhile to note that the implementation of the RFC8520 protocol (see *Manufacturer Usage Description*) would aid in preventing these remote access methods from working.

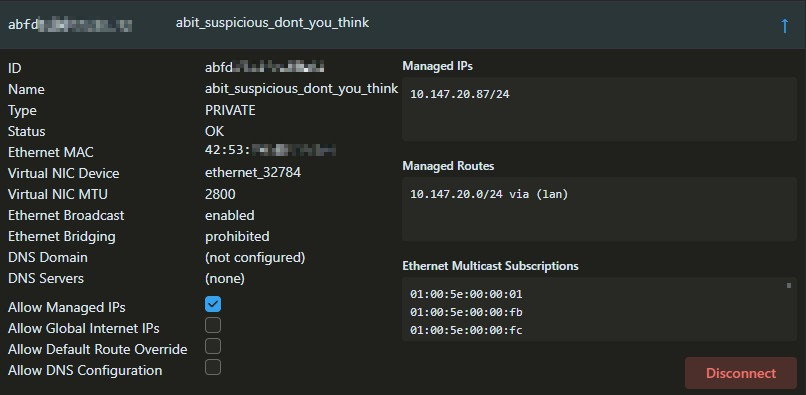


Figure – ZeroTier control panel

#### Reset Persistence

During the factory reset procedure (reset pin or boot failure), the recovery partition is flashed onto both system\_a and system\_b partitions. As this partition is modifiable, changes to the partition will be propagated to the system partitions after a factory reset. Modifications can therefore be performed by mounting the recovery partition while the system is live.  
A proof of concept has been made available[[29]](#footnote-30).

Candidate changes may include enabling SSH access, adding a backdoor user, remote access persistence patches, and the storage of additional tools like wget, curl, gdb, and strace.

#### Upgrade Persistence

During the firmware upgrade procedure, the system is updated in the following manner:

1. Download the update to UDISK
2. Extract update to download
3. Unmount system\_a / system\_b
4. Flash download to system\_a / system\_b
5. Boot into system\_a / system\_b
6. Flash download to system\_b / system\_a
7. Boot into system\_a / system\_b

Notably, both system\_a and system\_b partitions are completely overwritten, which would discard any changes or patches made on the device, inclusive of all previously stated methods.

A new method is proposed to achieve upgrade persistence, allowing modifications and other rooting artifacts to persist between upgrades. By hooking into the post-extraction stage of the firmware upgrade process (after step 2) and manipulating the contents of the download partition, upgrade-persistent changes can be performed – however this procedure is time-sensitive as the interception must occur between the start of the firmware extraction process (step 2) and the start of the image flashing process (step 4).

It is noted that interception tasks should complete as fast as possible, to best ensure that all changes will propagate to the system partitions during flashing. Where multiple changes are desired to be retained between updates, large sized files and time-bound functions can be offloaded onto the recovery or reserve partitions (see *Data Persistence*), where they can be processed during the runtime of the upgraded system. This offloading technique can dramatically decrease the number of required steps to perform upgrade persistence patching to a single step (i,e. creating a boot entry-point that calls the offloaded scripts)

Various techniques can be used to write to the download partition, such as a service worker, crontab or scheduled task – however one must be mindful of incurred CPU load should the technique incur a ‘busy-wait’. Binary patching of the SysUpdate could be performed as an alternative to a timed task and guarantee successful modification, however this method is complicated and likely prone to failure should the vendor perform unexpected updates to the binary. It should also be noted that upgrade persistence patching techniques must also handle future firmware upgrades, and thus must self-replicate its functionality.

# Chapter 6 | Discussion

## Commentary

In discussing the opinions on how manufacturers of IoT / smart home device have addressed the increasing concerns of digital privacy and product security, we comment on the collected results and findings, with reference to the [threat scenarios previously defined in Chapter 4](#_Chapter_4_|).

For ease of access, a summary of the threat scenario is provided below:

* TS0 – Concerned with the visibility and ownership of data and the device
* TS1 – Concerned with physical (proximal) threats e.g. supply chains, physical access
* TS2 – Concerned with remote (proximal) threats e.g. monitoring, device takeover
* TS3 – Concerned with remote (distal) threats e.g. backdoors, cloud services, the vendor

**System Design**

Regarding the embedded system design, Roborock’s decision to strip down their original Ubuntu Core based system to a more standard embedded Linux system significantly reduces the attack surface that may be exploited in scenario *TS2*, whereby the reduction in running processes consequently generate less network traffic that can be observed by an actor monitoring the network. Regarding *TS1* and *TS3*, the reduced set of available software and the omission of a package manager on the device additionally increases the effort required to sideload and run potentially malicious applications.

It is however emphasised that malicious intent is not prevented, but only slowed down. As such, in the case of *TS1* where periods extended access is possible (such as a supply chain attacks, or a malicious reseller), the device can still be modified to plant remote access persistence and grant an actor remote access even after possession of the device has been released.

**Process Privilege Level**

Regarding the privilege level of all processes running under the root account, security concerns are naturally raised for *TS1*, *TS2* and *TS3*, whereby a single vulnerability in any root-owned process can lead to system takeover. This threat is most prominent in *TS3*, as a vulnerability that lies in the cloud service communications would provide the means for an actor to gain control over any affected device over the internet. It is again noted that embedded system applications often run with system-level access (i.e. root) or in a root-less environment where all processes are effectively elevated – as it often mitigates hardware integration issues. Extreme care must therefore be taken when developing and securing such programs, however such attention to detail is difficult.

**Device Access**

Efforts to restrict access to the device via the serial terminal, ADB port and SSH shell are largely beneficial, as the restrictions significantly impede the ability to gain control of the device. In the case of *TS1* – ADB communications are restricted because of Roborock’s custom access control implementations and requires knowledge of a device-specific secret that can only be retrieved through tedious disassembly of the device, which is also required to access the UART pins that serve the serial terminal.

The long period of time required to disassemble, modify and reassemble the device severely decreases the capability for an actor to perform the modification over a number of devices. Large-scale modifications through supply chain attacks are only profitable between the stages of the flashing of the eMMC storage and the assembly of the device.

In the case of *TS2*, access to the device via SSH is prevented due to iptables rules. In later versions of the firmware, this restriction is enforced as observed through additional calls iptables from the WatchDoge and rrlogd binaries. Should the server be accessible for some reason, knowledge of the root password is still required which is unobtainable remotely.

It is noted that in the case of *TS0*, the security fortifications serve as hindrance to a device owner wanting to study or tinker with the device. The inability to use the ADB port and SSH server force an owner to disassemble the device and establish a UART connection, which may likely be out of technical ability for many owners who purchase this robot vacuum cleaner. Authentication flow modifications may potentially completely break access functionality for devices with outdated filesystem layouts, as was experienced with our device under test.

**Modifiable Recovery Partition**

Regarding the ability to modify the recovery partition, whilst useful under *TS0* (i.e. as a hardware hobbyist) to store software tools and maintain access between factory resets, security concerns are raised in the case of *TS1* – where the ability to modify the recovery partition raises the concern of backdoors being planted during the supply chain, or from a previous owner. Backdoors could eventually lead to the compromise of owner’s data, and of the owner’s network to which the targeted device is connected to. It is unlikely that an actor with only momentary physical access to the device will be able to exploit the reset persistence, due to the time required to disassemble and reassemble the device.

It is recommended that the recovery partition should be marked as ‘permanent read-only’ (Western Digital 2017) on the hardware eMMC level, as there is no need for the partition to be modified once the initial recovery image is flashed. Hardware write-protection provides the best method of data integrity as software-level write protection controls can be subverted (such as removing the ‘ro’ parameter from the Linux mount options).

Should the partition need to be modifiable for some reason, provisions to verify the authenticity of the filesystem should be enforced, such as some sort of signature verification or asymmetric encryption. Hardware security features like RPMB (Replay-Protected Memory Block) could serve to be beneficial, where writes to the storage medium must be paired with an authentication key that could be stored in an SE (Secure Element).

**Data Retention**

Whilst data in the UDISK (user data) partition is cleared securely during a factory reset, it is not cleared during a disassociation event (when the device is removed from a user’s account), despite the device acknowledging the event and entering access point mode. Under *TS0* and *TS1*, privacy concerns are raised – as an actor in possession of a recently disassociated device may be able to extract UGC and PII, inclusive of LIDAR mapping data, network credentials and network dumps. It would be advised for future firmware updates to delete and effectively factory reset the device when device disassociation is performed.

**Pairing Security**

The plain-text transmission of wireless credentials during initial device pairing raises concern for *TS2*, as anyone nearby who is monitoring wireless traffic will be able to eavesdrop and intercept the wireless credentials. The respective wireless network could then be joined using the intercepted credentials, allowing further access and enumeration into a victim’s network. Alarmingly, as there is no passphrase for the pairing access point – the wireless credentials within the pair request payload can be intercepted without even requiring the actor to join the same network, due to the behaviour of network traffic in an ‘Open’ wireless network.

It is recommended that the wireless network broadcasted during the device’s access point mode be secured with some wireless network security protocol, such as WPA2. Furthermore the pairing request should be encrypted, as stated in the Tuya security guidelines (2020). Whilst this specific privacy and security concern is only applicable during the pairing of the device, assumptions should not be made regarding the likelihood nor presence of a malicious actor nearby.

**Encryption of Logs**

Regarding the confidentiality of transmitted data, logs remain secure against *TS2*, even when the device is placed in an adversarial network condition such as a MITM proxy, or where TLS / SSL decryption is present – as logs are encrypted on the application-level. Whilst possible to visualise the flow of data and knowledge of network activity, the underlying data is ultimately protected with no way to view the decrypted contents without knowledge of the private key.

The application-encrypted logs are however ineffective against *TS1* and *TS3*, as the log sources are simply located within the filesystem. Access to any means to read the contents of files (whether it be serial, SSH, SFTP, ADB, reverse SSH or similar backdoor) will result in the ability to access log files before they are encrypted. In the case of the vendor, they possess the private decryption key, and hence will have unfiltered access to decrypt the log data.

In the case of *TS0*, the encryption of logs (and other transmitted data) is similarly trivial to a user wanting to view the nature and content of network traffic; however sufficient skill and technical knowledge is required to navigate a Linux filesystem, and optionally manually patch or dynamically instrument a process to hook into the pre-encryption or post-decryption stages.

**Packet Logging**

With the added implementation of the MSG\_LOG\_DEBUG\_\* signal in rrlogd, and the ability to perform a tcpdump packet capture in wlanmgr, privacy and security concerns are raised under *TS3*, as the activity of other devices on the same wireless network can be captured. As residential network traffic is often large and verbose, a great amount of flow detail can be obtained regarding the access to websites, frequency of website visits, the number of devices on a network, the types of devices on a network, and information about the network (such as the IP address). Whilst geographical lookups of IP address are often inaccurate, knowledge of the approximate region that the targeted device is in may aid in further exploitation.

**Privacy of Uploaded Data**

Concerns surrounding *TS0* and *TS3* are raised regarding the use of, and necessity to upload all the files from rrlogd. Whilst mapping data and packet logging data (as previously discussed) may be beneficial to the vendor, as to improve the cleaning functionality of the product, great trust must be placed in believing that the data is not misused or abused.

As discovered, log data was found to contain wireless credentials - despite the privacy policy stating that data of that type would not be kept remotely. Consequently, the need to verify company statements against their actions is stressed, with better transparency (and somehow confirmation) regarding the use of data. The flexibility to control the type of collected data is also desired, where privacy-minded owners can choose to opt-out / opt-in of certain log types.

## Response of Other Manufacturers

It is noted that whilst the Roborock S6 vacuum cleaner faces several privacy and security concerns, the company has made considerable effort to fortify their product against potential malicious threats. Privacy optimisations such as decreased log verbosity and application-level encryption was observed. Likewise, security fortifications such as overflow detection, signature verification and access control restrictions were noted. Additional steps can be taken by Roborock as a company however, to further improve their digital privacy and product security.

We turn to Xiaomi and Tuya for comparison, to investigate how other companies have addressed the increasing concerns for digital privacy and product security. Both Xiaomi and Tuya are large IoT ecosystem vendors who lease their infrastructure to white-label vendors and OEMs (like Roborock) as a subscription. Naturally, these ecosystem vendors are much larger in employee count, as both Xiaomi and Tuya have their own multi-staffed security teams.

As a result of their larger business (in both popularity, profit and employee count), these companies publicly promote the security research of their products and offer a bug bounty to incentivise research. Consequently, a high number of security vulnerabilities are discovered (as illustrated in Figure 48), allowing these companies to constantly issue security patches and fixes to better protect their products.

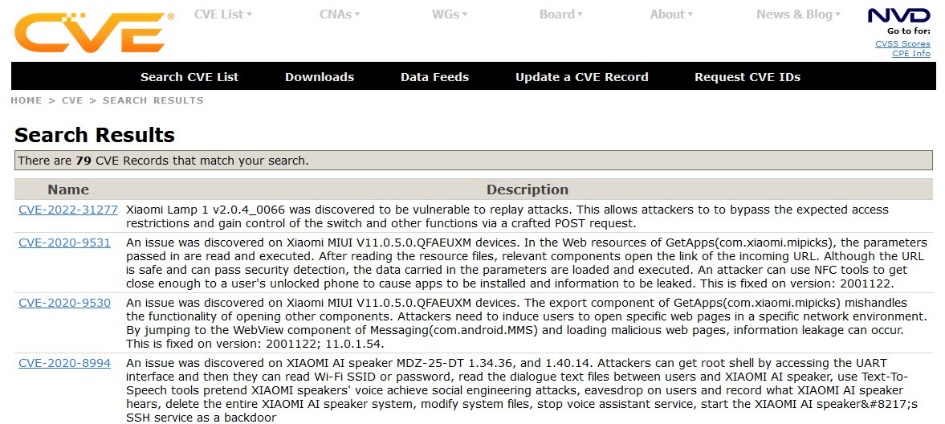


Figure – Screenshot of CVEs associated with Xiaomi

Whilst it is noted that Roborock is a small company, it is intriguing to see that only one security vulnerability was disclosed despite having released 13 different products since the company’s inception in 2014. Whilst is not mandatory for a company to publicly disclose their security vulnerabilities, it can conversely negatively illustrate the company’s security posture, as customers may be led to believe that the company is hiding its issues.

Both Xiaomi’s[[30]](#footnote-31) and Tuya’s[[31]](#footnote-32) security teams have additionally released white-papers regarding security minimums and guidelines for products that utilise their infrastructure. Despite the Roborock S6 vacuum cleaner utilising the Tuya infrastructure (through rriot\_tuya), the failure to encrypt the pairing traffic as outlined in the security guidelines raise concern to whether Tuya (and other IoT ecosystem vendors) perform security compliance checks on their white-label partners and OEMs before allowing a partner product to be verified and released.

We end our discussion involving other manufacturers by commenting on the adoption of the Manufacturer Usage Description protocol (RFC 8520), or rather why it hasn’t been widely adopted within the IoT and networking industry. Currently RFC 8520 does not seem to be adopted by any large IoT vendor, nor network equipment manufacturer. Despite Cisco spearheading the push for the use of MUD[[32]](#footnote-33), only their Catalyst line of network switches support the ‘Network Access Device’ role used in the MUD process.

It is likely that there is no incentive for IoT vendors to release MUD profiles of their devices, nor is there an incentive for networking equipment manufacturers to support RFC 8520 as there is no recent sign of activate development on any MUD-related projects. Furthermore, whilst UNSW’s Internet of Thing Research Group (EE&T)[[33]](#footnote-34) has contributed multiple MUD profiles for a variety of IoT devices, no other shared repository of MUD profiles exist – which further discourages companies from investing time and effort into implementing the specification. MUD profiles for the Roborock S6 were generated and are publicly available in the hopes of supporting the widespread adoption of RFC 8502.

## Conclusion

Through the firmware and network analysis from multiple firmware versions of the Roborock S6 vacuum cleaner, we conclude that Roborock has made efforts to secure their products and respect the privacy of their customers. Specifically, firmware upgrades incorporated changes to the ways in which device authentication and remote access was established, as to increase the difficulty and time required for local and remote threats to gain access to the device. Furthermore, in response to adversarial network conditions where a wireless network may be insecure, the confidentiality of transmitted log data was kept through application-level encryption that would remain given the presence of TLS / SSL decryption.

In the context of IoT and smart home device manufacturers in general, a ‘shift-left’ mentality to security research is encouraged – evident in the Xiaomi and Tuya each releasing security papers and offering bug bounty programs to promote the disclosure and reporting of vulnerabilities, as to patch and better protect their products.

Whilst these companies have made significant improvements to their product’s digital privacy and product security, further work is required to address the vulnerabilities and concerns raised in this thesis. Notably, IoT ecosystem vendors like Tuya need to perform (or improve) compliance checking procedures to ensure that their white-label vendors and OEM clients are in accordance with the security policies they released. Product vendors need to additionally review and verify their own policies (i.e. privacy policy) to ensure that their products are in accordance with their own policies even during upgrades, and that data is securely deleted in all expected scenarios. Furthermore, selective control over the nature and type of collected data should be given to the user. Modifications to a device’s storage should additionally be locked down, where write-access to base data and recovery firmware should be restricted unless mandatory.

In summary, manufacturers of IoT / smart home devices have addressed to privacy and security concerns by reacting with positive improvements and fixes, however better care must be taken to wholistically improve their privacy and security posture. The contributions offered from this thesis sought to critically analyse the security and privacy of the device, as to provide suggestions to ultimately improve the state of the art of IoT security and privacy research

**Limitations**

It is reiterated that the DUT used in the study was manufactured in June 2020, a year after official release of the Roborock S6 vacuum cleaner in 2019. Consequently, this thesis only covers the firmware versions from 2020 – 2022, notably failing to support the MiIO OTA exploit procedure.

Furthermore, the DUT’s manufacture month coincides date of the firmware version which used the migrated authentication flow, providing uncertainty as to whether later manufactured devices contained a modified filesystem structure that included files missing from the DUT’s filesystem.

## Future Work

Whilst a substantial amount of work was performed during this thesis, further topics of research are presented below which were beyond or after the scope of the study.

* Resilience of applications towards MITM and HSTS certificate pinning bypasses
* Security and strength of the asymmetric keys used
* Security and/or privacy assessment of the smartphone application
* Security and/or privacy assessment of the STM32 co-processor
* Fuzzing of program binaries to find more vulnerabilities
* Dynamic instrumentation of program binaries using Frida
* Upgrade analysis of new firmware versions after v02.29.02
* Analysis of other Tuya-integrated vacuum cleaners

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Appendix

Appendix – rrlogd log scope excerpt (v01.15.58)

|  |  |
| --- | --- |
| **Archive** | **Contents** |
| varlog.tar.gz (tar\_extra\_file.sh) | /var/log/upstart |
| /var/log/boot.log |
| /var/log/bootdmesg |
| /var/log/dmesg |
| /var/log/faillog |
| /var/log/kern.log |
| /var/log/lastlog |
| /var/log/rr\_try\_mount.log |
| /var/log/syslog |
| misc.gz  (misc.sh) | date |
| /dev/jiffies |
| /proc/interrupts |
| /proc/softirqs |
| dmesg |
| /proc/meminfo |
| /proc/vmstat |
| /proc/slabinfo |
| /proc/zoneinfo |
| /proc/pagetypeinfo |
| /sys/devices/system/cpu/cpu0/cpufreq/stats/time\_in\_state |
| /sys/devices/system/cpu/cpu1/cpufreq/stats/time\_in\_state |
| /sys/devices/system/cpu/cpu2/cpufreq/stats/time\_in\_state |
| /sys/devices/system/cpu/cpu3/cpufreq/stats/time\_in\_state |
| df -h |
| lsof / |
| lsof /dev |
| lsof /tmp |
| lsof /run |
| lsof /run/lock |
| lsof /run/shm |
| lsof /mnt/updbuf |
| lsof /mnt/data |
| lsof /mnt/reserve |
| lsof /mnt/default |
| /sys/devices/platform/uart.0/ctrl\_info |
| /sys/devices/platform/uart.0/status |
| /sys/devices/platform/uart.1/ctrl\_info |
| /sys/devices/platform/uart.1/status |
| /sys/devices/platform/uart.2/ctrl\_info |
| /sys/devices/platform/uart.2/status |
| watchdog.gz | watchdog.log |
| rrlog.gz | rrlog.log |
| miio.gz | miio.log |
| SLAMMAP.tar.gz | \*.ppm |
| SYSUPD\_normal\_updater.tar.gz | SYSUPD\_updater\_pid\*.log |
| varlog.tar.gz | varlog.tar.gz (itself) |
| mt\_test.tar.ss.gz | /mnt/data/rockrobo/Mt\* |
| /mnt/data/rockrobo/mt\* |
| uarttest.tar.ss.gz | /mnt/data/rockrobo/noupload/uart\_test\* |
| boot\_reason.gz | boot\_reason |
| crashlog.gz | crashlog |

Appendix - rr\_login authentication loop (v02.29.02)

A screenshot of a computer

Description automatically generated with medium confidence

1. <https://www.shodan.io/search?query=webcam> [↑](#footnote-ref-2)
2. <https://global.roborock.com/pages/disclosure-security-vulnerability-on-tuya-iot-cloud> [↑](#footnote-ref-3)
3. <https://www.espressif.com/en/products/socs/esp8266> [↑](#footnote-ref-4)
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    [↑](#footnote-ref-5)
5. <https://github.com/dgiese/dustcloud> [↑](#footnote-ref-6)
6. <https://github.com/nabla-c0d3/ssl-kill-switch2> [↑](#footnote-ref-7)
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    See <https://github.com/marcelrv/XiaomiRobotVacuumProtocol/blob/master/RRMapFile/RRFileFormat.md> [↑](#footnote-ref-20)
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22. https://frida.re/ [↑](#footnote-ref-23)
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