Concordia Institute for Information System Engineering (CIISE)

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INSE 6540: Internet of Things Security

Project Report: Security mitigation solutions for IoT

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Smart Home

A smart home is a platform where it connects various electronic home appliances and devices via network. From waking up with the automated alarm to going to bed with autonomous air conditioning, everything in between could be done using the IoT enabled smart devices which offers flexible adoption and wide acceptance.[1] These devices, appliances, and sensors that can be remotely accessed, monitored, and controlled and that provide services responding to the residents' needs. [2]

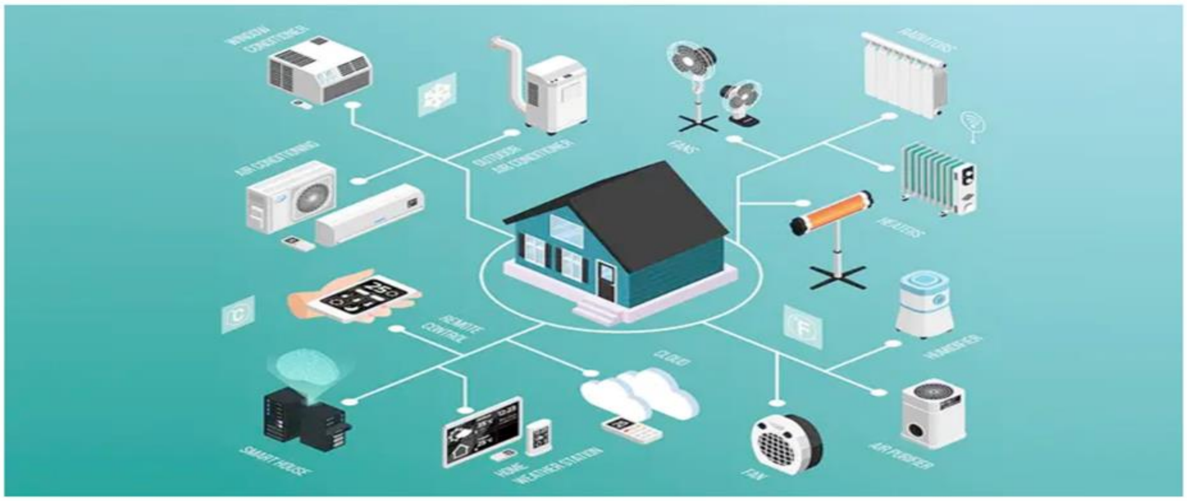
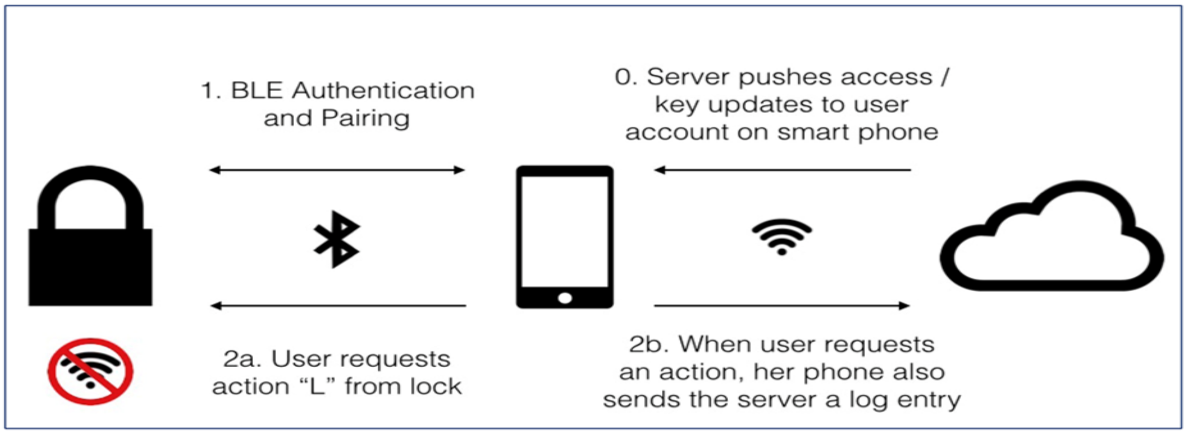


Fig 1: Smart home layout

IoT devices mainly follow two kinds of architecture.

Device Gateway Cloud (DGC): In this architecture smart appliances communicate with the server through mobile and those appliances are connected to mobile using Bluetooth.


1. BLE Authentication and Pairing
0. Server pushes access / key updates to user account on smart phone
2a. User requests action "L" from lock
2b. When user requests an action, her phone also sends the server a log entry

Direct Internet Connection: In this scenario smart appliances have direct internet connection, and it can sync with the server in real time. [3]

These two designs serve as the foundation for all other smart house architectures, but there are many different variants with distinct kinds of capability and security threads. Among them these three are the most significant and prominent architectures: middleware, cloud and gateway architectures.

Middleware architecture: In the context of the Internet of Things, middleware is the software layer that lies between the application layer and the hardware (sensors, devices), offering services to make it easier to integrate, manage, and communicate with IoT devices. It offers a more standardized and adaptable approach to developing Internet of Things applications by helping simplify the complexity of the underlying hardware and network layer.

Cloud Architectures: IoT cloud architectures by utilizing scalable cloud resources, smart homes facilitate effective data management, processing, and storage while guaranteeing smooth integration and control of smart devices. For smart home environments, they offer increased security, scalability, and flexibility to meet changing demands.

Gateway Architectures: The design and construction of gateway devices, which serve as a bridge between IoT devices and the cloud or other networks, are referred to as gateway architectures in IoT systems. These gateways are essential for maintaining security, controlling communication, and handling data locally.[4]

MQTT (Message Queuing Telemetry Transport)

MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol designed for efficient communication in IoT (Internet of Things) environments. It operates on a publish/subscribe model allowing devices known as clients, to publish data to specific topics or subscribe to topics of interest, receiving only relevant information. Central to this architecture is the MQTT broker, which facilitates the communication by receiving messages from publishers and routing them to the appropriate subscribers. MQTT's design prioritizes low bandwidth usage and minimal network overhead, makes it ideal for scenarios where network resources are limited, or connections are unreliable. MQTT can also be secured using SSL/TLS encryption and supports authentication mechanisms to safeguard data transmission. These attributes make MQTT a popular choice in IoT applications ranging from smart homes and healthcare devices to industrial automation, where reliable, efficient, and secure communication is crucial.

Vulnerabilities in Smart Home Systems

The proliferation of smart home technology has revolutionized domestic life, offering unparalleled convenience and automation. However, the integration of numerous interconnected devices within these environments has also introduced significant cybersecurity challenges. As the number of internet-connected devices in homes increases, so does the potential attack surface for malicious actors. This section explores various types of attacks on smart homes, presenting detailed case studies and emphasizing the critical need for comprehensive security measures.

Smart home devices, including thermostats, security cameras, and smart locks, typically have limited processing power and security features. These devices are often connected to the internet and communicate over home networks. Due to the lack of robust security protocols, these devices are susceptible to various cyberattacks, which can lead to unauthorized access, data breaches, and even physical security threats to the occupants of the home.

The inherent vulnerability of smart home systems is exacerbated by their interconnected nature. A single compromised device can act as a gateway for attackers to infiltrate the entire network, leading to potentially severe consequences. The following sections provide an in-depth examination of several types of attacks that have been documented in smart homes.

i) Privacy and Security Threats Due to Interconnected Devices

One of the most significant concerns in smart home environments is the security risk posed by interconnected devices, especially those with limited processing capabilities. Attackers can exploit these weaknesses to gain unauthorized access to home networks, where they can monitor activities, steal sensitive information, or control various devices.

Case Study: Shi et al. [5] documented an attack in 2016 in which hackers targeted a smart home by exploiting a vulnerability in a smart light bulb that had outdated firmware. Once the attackers gained access to the network through this device, they were able to monitor the home's activities, access live feeds from security cameras, and even take control of other connected devices. This incident underscored the significant risk posed by a single compromised device within an interconnected network, as it can potentially lead to a broader and more severe security breach.

Impact: The case highlights the importance of implementing regular firmware updates, using network segmentation to limit the spread of potential intrusions, and adopting more secure communication protocols within smart home ecosystems. These measures are essential to mitigate the risks associated with the interconnected nature of smart home devices.

ii) Distributed Denial of Service (DDoS) Attacks: Mirai, KRACKs, BrickerBot

Distributed Denial of Service (DDoS) attacks are among the most prevalent threats to Internet of Things (IoT) devices, including those found in smart homes. These attacks involve overwhelming a target device or network with excessive internet traffic, rendering it unresponsive or inoperative.

Case Study: Zhang et al. [6] provide an account of the infamous 2016 Mirai botnet attack, a classic example of a DDoS attack that leveraged IoT devices. The Mirai botnet infected thousands of devices, such as security cameras and routers, by exploiting default login credentials that were left unchanged by users. These compromised devices were subsequently used to launch large-scale DDoS attacks, the most notable of which targeted the DNS provider Dyn, causing widespread internet service disruptions across major websites like Twitter, Netflix, and Reddit. Similarly, the KRACK (Key Reinstallation AttaCK) vulnerability and the BrickerBot malware exploited weaknesses in Wi-Fi encryption protocols and device integrity, respectively, further exposing the fragility of smart home ecosystems.

Impact: These incidents emphasize the critical need for enhancing the security of IoT devices through stronger password policies, routine security updates, and the use of secure encryption protocols. Ensuring that these devices are protected from being co-opted into botnets is essential for maintaining the integrity and functionality of smart home systems.

iii) Man-in-the-Middle (MitM) Attack

A Man-in-the-Middle (MitM) attack occurs when an attacker intercepts and potentially alters the communication between two devices without the knowledge of the users involved. In the context of smart homes, such attacks can have severe consequences, as they may allow attackers to manipulate device settings or gain unauthorized access to sensitive information.

Case Study: Perez [7] reported a MitM attack in 2019 involving a smart thermostat. In this case, attackers intercepted the communication between the thermostat and the central home network, exploiting vulnerabilities in the communication protocol. By doing so, they were able to alter the temperature settings within the home and gain access to other connected devices. This breach demonstrated how even seemingly benign devices, such as thermostats, could become entry points for more extensive network intrusions.

Impact: This case underscores the necessity of implementing secure communication protocols, such as HTTPS and end-to-end encryption, to safeguard against MitM attacks. Furthermore, it highlights the importance of continuous network monitoring to detect and respond to suspicious activities promptly, thereby minimizing the potential damage from such breaches.

iv) Unauthorized Access

Unauthorized access to smart home devices is an increasingly prevalent concern, particularly as more devices become integrated with cloud services. When attackers gain unauthorized access to these devices, they can control them remotely, posing significant security risks to homeowners.

Case Study: Liyanage et al. [8] described a 2020 incident where a homeowner in the United States experienced unauthorized access to their smart lock system. The attackers exploited a vulnerability in the cloud service used by the smart lock manufacturer, allowing them to unlock the home remotely. The homeowner only discovered the breach after noticing unusual access logs in their smart home application. This incident highlights the vulnerability of smart home devices that rely on cloud services for their functionality.

Impact: This case illustrates the importance of securing cloud-based IoT services with multi-factor authentication (MFA) and other robust security measures to prevent unauthorized access. It also underscores the necessity of having backup security options, such as physical keys, to ensure continued access and security in the event of a system compromise.

As the adoption of smart home technology continues to grow, so too do the risks associated with its use. The case studies presented in this section highlight the various ways in which smart homes can be targeted by cyberattacks, from exploiting vulnerabilities in individual devices to orchestrating large-scale network attacks. To effectively mitigate these risks, it is crucial to implement a comprehensive approach to security, including regular software updates, the use of strong encryption and authentication methods, and the strategic segmentation of home networks. By taking these steps, homeowners can better protect their smart home environments from the increasingly sophisticated cyber threats that they face.

v) Case Study: Securing IoT in Smart Cities - A Real-World Implementation of Distributed Ledger Technology

This case study focusses on the deployment of cybersecurity measures in Taipei, Taiwan's smart city infrastructure. The city had begun to be sought out to develop into a smart city by incorporating IoT. This connection had posed a number of hurdles for them, including data privacy concerns, unauthorised access, vulnerability to IoT-based DDoS assaults, and so on [2]. To address these challenges that they would face, Taipei collaborated with the company IOTA, a technology startup specialising in distributed ledger technology (DLT), specifically they used a technology called Tangle, a third-generation blockchain technology that facilitates transactions maintained in a directed acyclic graph (DAG) format [9].

Implementation Details : Tangle's decentralized architecture enhanced IoT security by assigning unique identities to devices, ensuring transaction integrity and privacy through encrypted data storage accessible only via decryption keys. It enabled real-time micro-transactions, crucial for tasks like traffic management, and its distributed design provided strong resilience against DDoS attacks, making large-scale network compromises nearly impossible.

Results and Impact: The implementation of Tangle technology significantly enhanced the security and privacy of IoT devices, protecting crucial infrastructure data. This secure IoT network enabled Taipei to improve the efficiency of its civic operations leading to better traffic management, quicker emergency responses, and reduced energy consumption in public lighting. Additionally, the robust security measures increased public trust in digital services and facilitating greater adoption of smart city programs.[10]

Security Mitigation Solutions for IoT Threats

IoT devices are usually lightweight and have limited processing power, memory, and storage. This limitation makes it difficult to deploy the strong security measures, making devices vulnerable to a variety of privacy and security risks. Also, because IoT devices are interconnected, a vulnerability in one device might end up in resulting in a larger network breach, which could allow attackers to exploit the system's weakest link.

Edge Computing: With this processing can be offloaded to edge devices with additional computational capability, such as gateways or edge servers, to reduce the stress on the IoT devices. Processing and analysing data at the edge will decrease the raw data exposure and limit all the sensitive information transferring over the network.

Lightweight Cryptography: Implementing lightweight encryption methods developed specifically for resource-constrained devices could prove to be critical. These algorithms maintain data confidentiality, integrity, and authenticity without using the device's limited resources. Some example are Advanced Encryption Standard (AES) with smaller key sizes and the usage of Elliptic Curve Cryptography (ECC).

Network Segmentation: Segregating IoT devices into discrete network segments can also help to mitigate the consequences of a security breach. Virtual LANs (VLANs) or software-defined networking (SDN) can be used to group devices based on their function or sensitivity level, limiting unauthorised access to vital systems from less secure devices.

Firewalls and Intrusion Detection Systems (IDS): Firewalls and IDS deployed at the network's edge can monitor and filter out the traffic, detecting and blocking suspicious activity. This strategy could prove to be critical for limiting lateral movement of threats within the network and protecting sensitive data present.

Implementing security certificates: The process of implementing security certificates in the Internet of Things (IoT) entails the issuance of digital certificates for devices by a reputable

Certificate Authority (CA), which facilitates secure and authenticated communication. This approach guarantees that data exchanges are encrypted and safeguarded from unauthorized access. Ensuring that only trusted devices can interact within the network, it encompasses processes for certificate renewal, revocation, and secure device onboarding. This method improves the overall security and scalability of IoT environments by optimizing for resource-constrained devices and adhering to industry standards.

End-to-End Encryption: Using end-to-end encryption ensures that data could be exchanged between IoT devices and servers is encrypted and unreadable to anyone who intercepts it. TLS and DTLS are two protocols that enable strong encryption for IoT connectivity.

Mutual Authentication: Mutual authentication is also a good choice, it requires devices and servers to authenticate each other before transferring data. This can be accomplished with the use of certificates, tokens, or public key infrastructure (PKI). Mutual authentication prevents unauthorized devices from entering the network and ensures that the communication is only established with trusted entities.

Anomaly Detection Systems (ADS): Using ADS, anomalous traffic patterns can be detected that could signal a MitM attack. For example, if a device were to begin connecting with an unexpected IP address or displays irregular data transmission behaviour, the system can notify administrators to take corrective action. Continuously monitor network traffic for unusual activity and maintain logs to detect and respond to potential MitM attacks promptly.

Secure Key Management: The proper management of encryption keys is critical in preventing MitM attacks. Keys should be securely maintained, and key exchange methods like Diffie-Hellman should be used to prevent key interception during transmission.

Network Segmentation: To minimize vulnerability and minimize the effect of possible attacks, IoT devices may be isolated on different network segments.

Multi-Factor Authentication (MFA): MFA is a great and commonly used way that increases security by requiring users to give two or more verification factors (e.g., password and biometric) before accessing IoT devices or systems. This lowers the chance of unauthorised access, even if login credentials are compromised.

Role-Based Access Control (RBAC): RBAC controls the access to IoT devices and systems based on the user's job within an organisation. By defining particular roles and permissions or attributes, RBAC guarantees that the users only have access to the resources required for their position, reducing the risk of unauthorised access to sensitive data or systems.

System design and development

The primary objective of the hardware implementation part was to build a secure and efficient simulated smart home environment using a combination of IoT devices and an open-source platform. In our setup, we simulated a garage within the smart home that opens when motion is detected and triggers a buzzer. However, an attacker could potentially intercept the MQTT messages as they are not encrypted by default. The attacker could achieve this by using Wireshark and a Wi-Fi dongle operating in monitor mode to sniff the network traffic. Finally, we have mitigated this vulnerability by encrypting the MQTT message so that it cannot be intercepted in clear text.

Overall, the system is designed to automate certain tasks, monitor security, and ensure data privacy through effective device integration and communication protocols.

Core Hardware Components

i) Raspberry Pi 4: The Raspberry Pi 4 serves as the central hub for the smart home system. In our setup The Raspberry Pi 4 hosts Home Assistant OS and the MQTT broker, acting as the command center that processes inputs from various sensors, executes automation routines, and relays commands to other devices like the ESP32 module and smart cameras. This tiny single board computer is equipped with a quad-core ARM Cortex-A72 CPU that provides sufficient processing power for handling multiple IoT tasks simultaneously.

Fig 2: Raspberry Pi 4B

ii) ESP32 Module: The ESP32 is a low-cost, low-power microcontroller with integrated Wi-Fi and Bluetooth capabilities. It is known for its versatility and is widely used in IoT projects for controlling peripheral devices and sensors. It comes with a dual-core processor, a range of GPIO (General Purpose Input/Output) pins, and support for various communication protocols like SPI, I2C, and UART. In this project, the ESP32 module is used as a node to control additional devices such as buzzers, which are triggered by events like motion detection. It receives commands from the Home assistant via MQTT and executes the appropriate actions.

Fig 3: ESP 32 Module

iii) Imou Ranger 2 Smart IP Camera: The Imou Ranger 2 is a smart IP camera designed for home security. It provides high-definition video streaming and real-time motion detection. The camera offers 1080p video resolution, night vision capabilities, and a 360-degree pan and tilt feature. In our setup, the camera is integrated into Home Assistant via the HACS (Home Assistant Community Store) library. It continuously monitors for motion and triggers automation routines within Home Assistant, such as sending alerts to the user or activating the ESP32-controlled buzzer.

Fig 4 : Imou Ranger 2 Camera

iv) Mikrotik Router: The Mikrotik RBD52G Router is a sophisticated, enterprise-grade router that will manage the local network in our project. The Router connects all devices in the smart home network, including the Raspberry Pi 4, ESP32 module, and Imou camera, to the internet and to each other.

Fig 5: Mikrotik RBD52G Router

Integration and Communication

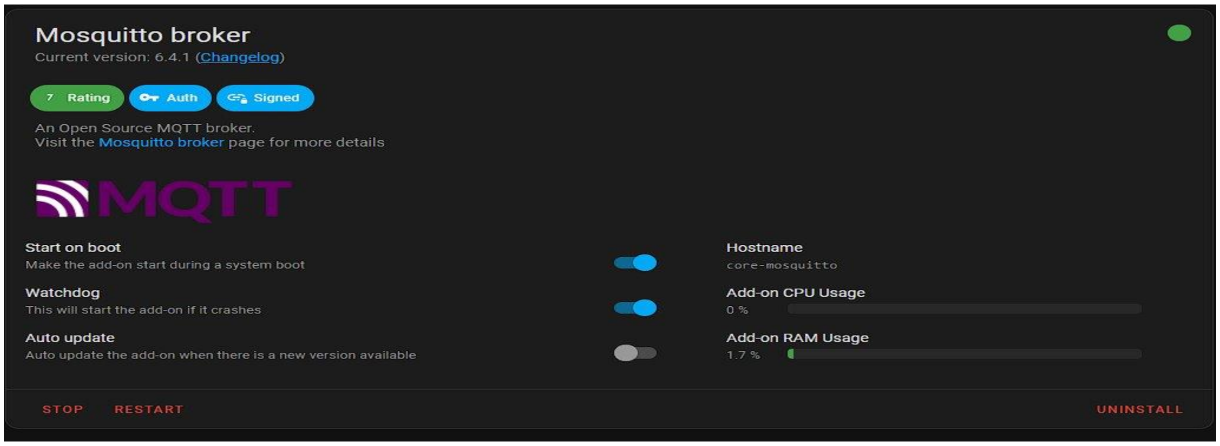
The integration of these components is facilitated through Home Assistant that serves as the software layer that connects and manages the hardware devices. MQTT (Message Queuing Telemetry Transport) is used as the communication protocol between the Raspberry Pi, ESP32 module, and other devices. MQTT's lightweight nature and publish/subscribe model make it ideal for the low-power, low-bandwidth requirements of IoT systems.

The Mikrotik Router ensures that all communications are routed, while the Raspberry Pi acts as the central processor that manages data flow and device interactions through Home Assistant. Together, these components create a cohesive smart home environment for our testing purpose.

System Setup

Home Assistant Installation: Home Assistant acts as the brain of our system by managing the interactions between various components. It also provides a user-friendly interface for monitoring and controlling the system. It was chosen as the central platform for managing the smart home ecosystem due to its flexibility, wide device support, and strong community assistance. The installation involved flashing the Home Assistant OS onto a microSD card through the Raspberry pi imager. Once powered up, the system was configured via a web interface. Followed by, we set up the necessary integrations and automations for the smart home devices.

MQTT Broker Integration: MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol specifically designed for low-bandwidth, high-latency networks that is ideal for IoT applications. The protocol's publish/subscribe model allows devices to communicate efficiently and reliably. The MQTT broker was added as an add-on in Home Assistant. We choose a popular open-source MQTT broker Mosquitto. The broker facilitates communication between the Raspberry Pi 4, ESP32 module, and other IoT devices.


Mosquitto broker
Current version: 6.4.1 (Changelog)

An Open Source MQTT broker.
Visit the Mosquitto broker page for more details

Start on boot
Make the add-on start during a system boot

Watchdog
This will start the add-on if it crashes

Auto update
Auto update the add-on when there is a new version available

Hostname
core-mosquitto

Add-on CPU Usage
0 %

Add-on RAM Usage
1.7 %

Figure 6: Mosquito Broker add on integration

MQTT allows the devices in the network to publish messages to specific topics, which other devices or services can subscribe to. This setup accounts for real-time communication between devices for the automation processes in the smart home setup.

Imou Ranger 2 Camera Integration: The Imou Ranger 2 Smart IP Camera was integrated into the Home Assistant ecosystem to provide real-time video surveillance and motion detection capabilities. By default, this camera is a proprietary hardware and is not supported in the Home Assistant. However, we integrated it with the platform using the HACS (Home Assistant Community Store) library which supports a wide range of third-party devices and services.

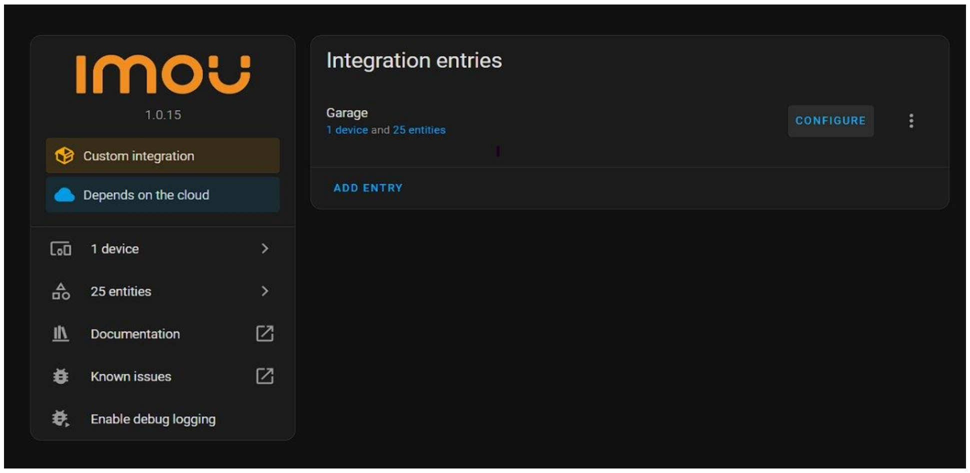


Figure 7: IMOU camera integration with Home Assistant.

Along with numerous automation options, the motion detection feature of the camera can trigger predefined automations such as sending alerts to the user or activating the ESP32 module to sound an alarm.

ESP32 Module and Buzzer Configuration: The ESP32 module is known for its low power consumption and versatile connectivity options. We programmed it to control a buzzer that serves as an alert mechanism in the system. The ESP32 was programmed using the Arduino IDE to subscribe to specific MQTT topics. When a motion detection event is published by the Home assistant upon getting data from Imou cloud, the ESP32 receives the message and triggers the connected buzzer.

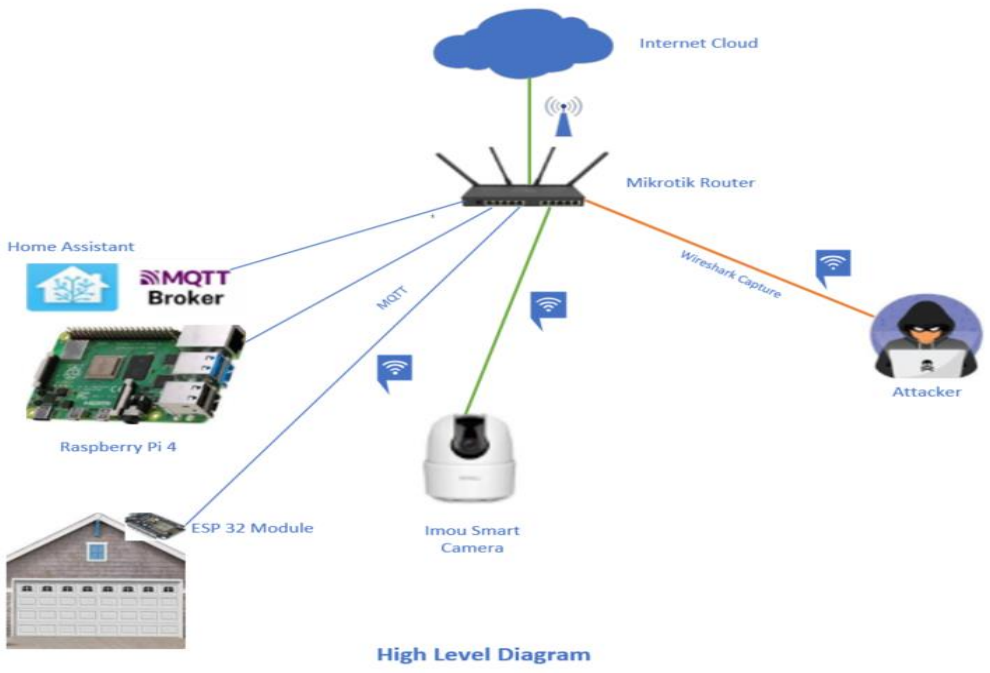


Figure 8: High Level Diagram of the setup

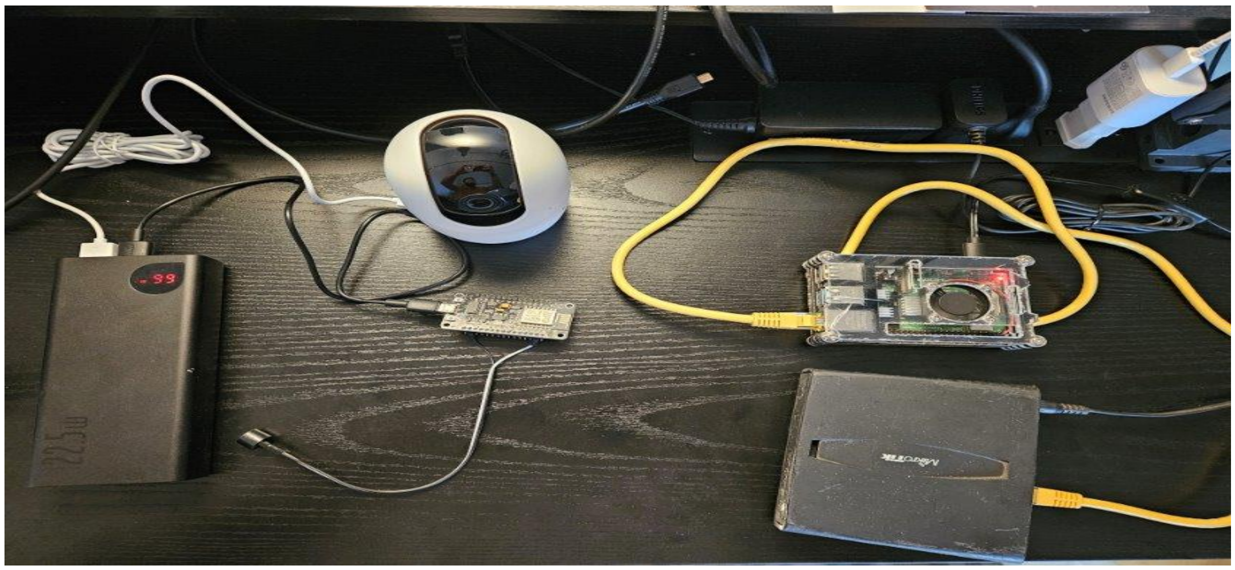


Figure 9: Real Life Setup

Security Testing Tools

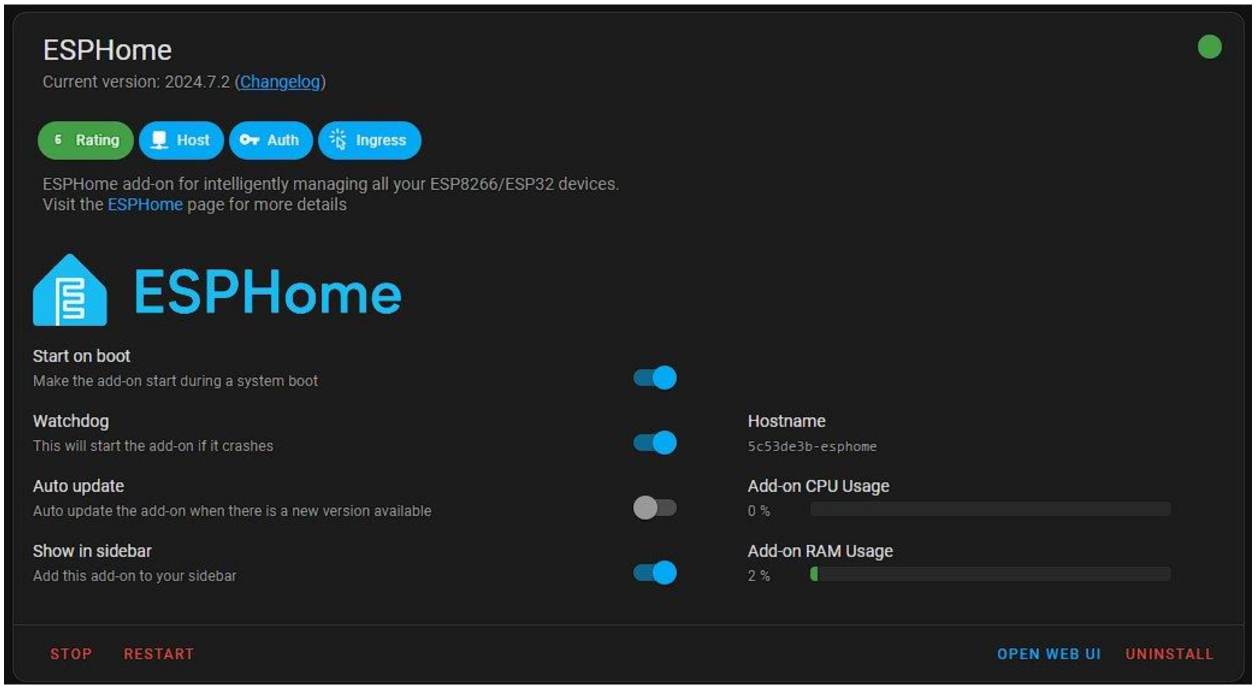
Wireshark Analysis: Wireshark is a powerful network protocol analyzer that we used to monitor the network traffic within the system. Particularly, our focus was on capturing MQTT messages to assess their security. A Wi-Fi dongle in monitoring mode was used to capture MQTT packets being transmitted between the Raspberry Pi 4 and the ESP32 module. The analysis revealed that these messages including sensitive credentials were initially transmitted in clear text.

This Wireshark analysis highlighted the need for stronger encryption methods within the IoT network to prevent unauthorized access and data breaches by an attacker who has access to the local network.

TLS Encryption Implementation: To address the security vulnerabilities identified during the Wireshark analysis, TLS (Transport Layer Security) 1.2 encryption was implemented for MQTT communications within the network. TLS was configured on the MQTT broker within Home Assistant through self-signing certificate. This involved generating and installing the certificate on the broker and clients. The implementation of TLS encryption mitigated the security risks since sensitive data such as MQTT credentials and messages were no longer exposed in clear text. Subsequent Wireshark captures confirmed that the encrypted messages could not be deciphered by potential attackers.

The high-level diagram provides a visual representation of the smart home system's architecture, and the interaction between various components and the data flow within the network.

Home Assistant Configurations and Navigation


ESPHome

Current version: 2024.7.2 (Changelog)

ESPHome add-on for intelligently managing all your ESP8266/ESP32 devices.
Visit the ESPHome page for more details

Start on boot
Make the add-on start during a system boot

Watchdog
This will start the add-on if it crashes

Auto update
Auto update the add-on when there is a new version available

Show in sidebar
Add this add-on to your sidebar

Hostname
5c53de3b-esphome

Add-on CPU Usage
0 %

Add-on RAM Usage
2 %

Figure 10: ESPHome Add on Setup in Home Assistant

Motion Detection Trigger: The Imou Ranger 2 Smart IP Camera was integrated into Home Assistant, allowing it to function as a motion detection sensor within the smart home environment. Using the HACS (Home Assistant Community Store) library, the camera was added as a device entity in Home Assistant.

A specific automation rule was configured in Home Assistant to monitor the camera for motion detection. When the Imou cloud detects a motion through the data sent by the camera, Home Assistant automatically triggers a series of pre-defined actions within the system.

ESP32 Activation: An automation rule was created in Home Assistant that links the motion detection event from the Imou camera to the ESP32 module. Upon detecting motion, it publishes an MQTT message.

The ESP32 module is subscribed to the relevant MQTT topic and activates the connected buzzer. This immediate audible response serves as a deterrent to potential intruders and alerts the homeowner to possible security breaches since we are assuming that the Garage may provide a shorter route to access the home resulting more damage beyond the cyberspace.

User Notifications: We also configured the home assistant to send instant notifications to the user’s mobile device whenever motion is detected by the Imou camera. These notifications include details of the event, such as the time of detection and the specific camera involved.

Dashboard Overview:

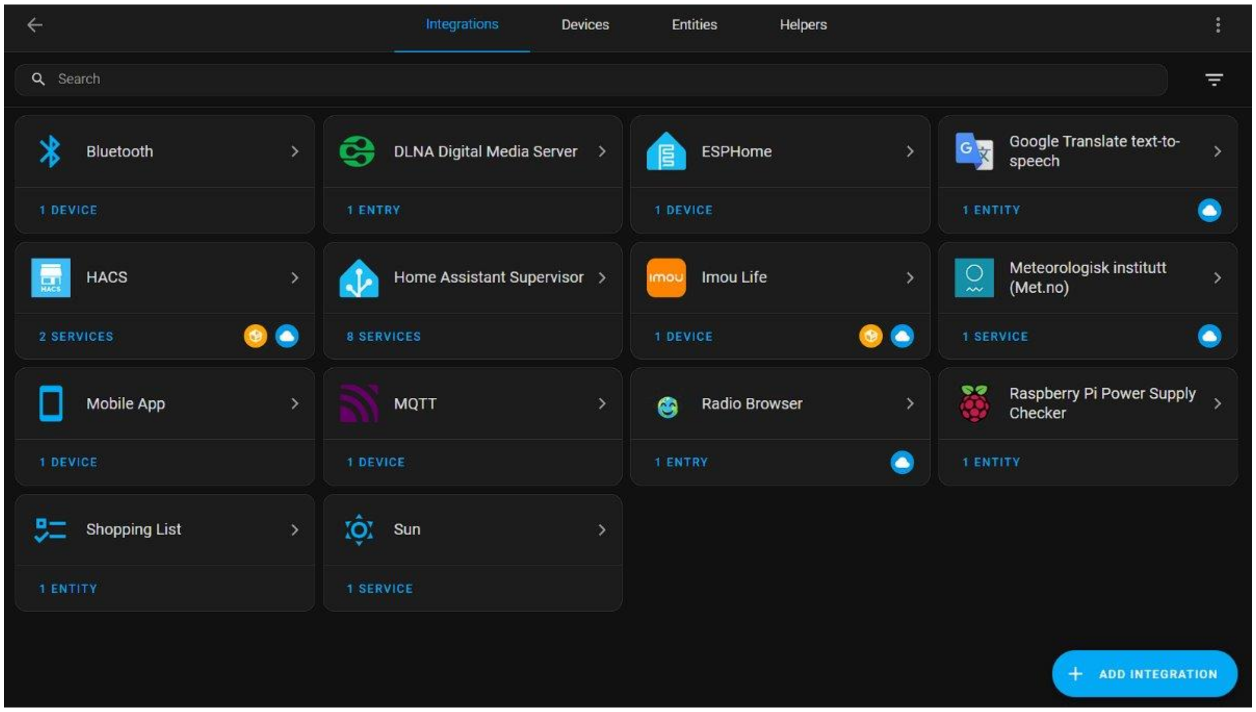


Figure 11: Home Assistant Integrations: overview of connected devices and services like MQTT, Imou Life, and ESPHome.

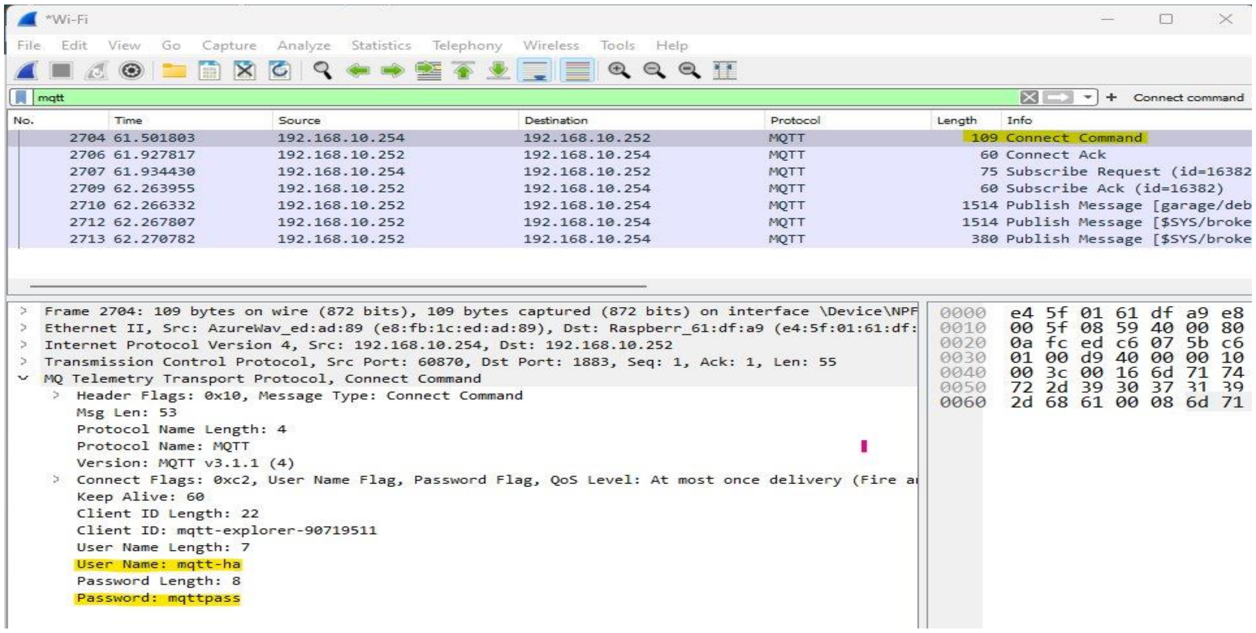
The Home Assistant dashboard is the primary interface through which users interact with their smart home system. It provides an overview of all connected devices, their status, and any ongoing automations. The dashboard allows users to monitor the real-time status of devices, such as whether the garage door is open or closed, if the alarm is armed, or if motion has been detected.

MQTT Vulnerability Exploitation via Wireshark

MQTT (Message Queuing Telemetry Transport) is widely used in IoT environments due to its lightweight and efficient messaging capabilities. However, without proper security measures MQTT can expose significant vulnerabilities such as the transmission of sensitive data in clear text.

Monitoring Mode: To capture the network traffic within the smart home environment, a Wi-Fi dongle capable of operating in monitoring mode was used. This setup allowed us to intercept and analyze all MQTT packets being transmitted between the IoT devices on the local network. Since the Raspberry Pi 4 hosts the MQTT broker, and the ESP32 module subscribes to MQTT topics, they were the primary targets for this analysis. By capturing the traffic between these devices, we could examine the content and structure of the MQTT messages being exchanged.

MQTT Message Capture: Using Wireshark, we captured and inspected the MQTT messages transmitted over the network. These packets included various MQTT control packets such as CONNECT, PUBLISH, SUBSCRIBE, and others, which are used to manage the communication between the broker and clients. Upon analyzing the captured packets, it was visible that MQTT messages, including critical information like usernames, passwords, and payload data, were being transmitted in clear text. This unencrypted transmission presents a significant security risk, as any attacker with access to the network could potentially intercept and misuse this information.


*Wi-Fi
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
mqtt
Connect command

```
No.         Time          Source              Destination         Protocol    Length  Info
      2704 61.501803     192.168.10.254      192.168.10.252      MQTT           109 Connect Command
      2706 61.927817     192.168.10.252      192.168.10.254      MQTT            60 Connect Ack
      2707 61.934430     192.168.10.254      192.168.10.252      MQTT            75 Subscribe Request (id=16382
      2709 62.263955     192.168.10.252      192.168.10.254      MQTT            60 Subscribe Ack (id=16382)
      2710 62.266332     192.168.10.252      192.168.10.254      MQTT          1514 Publish Message [garage/deb
      2712 62.267807     192.168.10.252      192.168.10.254      MQTT          1514 Publish Message [$SYS/broke
      2713 62.270782     192.168.10.252      192.168.10.254      MQTT           380 Publish Message [$SYS/broke
```

```
> Frame 2704: 109 bytes on wire (872 bits), 109 bytes captured (872 bits) on interface \Device\NPF
> Ethernet II, Src: AzureWav_ed:ad:89 (e8:fb:1c:ed:ad:89), Dst: Raspberr_61:df:a9 (e4:5f:01:61:df:
> Internet Protocol Version 4, Src: 192.168.10.254, Dst: 192.168.10.252
> Transmission Control Protocol, Src Port: 60870, Dst Port: 1883, Seq: 1, Ack: 1, Len: 55
v MQ Telemetry Transport Protocol, Connect Command
   > Header Flags: 0x10, Message Type: Connect Command
     Msg Len: 53
     Protocol Name Length: 4
     Protocol Name: MQTT
     Version: MQTT v3.1.1 (4)
   > Connect Flags: 0xc2, User Name Flag, Password Flag, QoS Level: At most once delivery (Fire a
     Keep Alive: 60
     Client ID Length: 22
     Client ID: mqtt-explorer-90719511
     User Name Length: 7
     User Name: mqtt-ha
     Password Length: 8
     Password: mqttpass
```

```
0000  e4 5f 01 61 df a9 e8
0010  00 5f 08 59 40 00 80
0020  0a fc ed c6 07 5b c6
0030  01 00 d9 40 00 00 10
0040  00 3c 00 16 6d 71 74
0050  72 2d 39 30 37 31 39
0060  2d 68 61 00 08 6d 71
```

Figure 12: MQTT Capture in plaintext via Wireshark

Among the most alarming findings was the exposure of MQTT credentials in the initial CONNECT command sent by the client (ESP32 module) to the broker (Raspberry Pi 4). The username and password used for authentication were visible in plain text within the packet data. The exposure of these credentials means that an attacker who successfully captures these packets could gain unauthorized access to the MQTT broker. This would allow them to publish or subscribe to topics, potentially disrupting the smart home system or gaining control over connected devices.

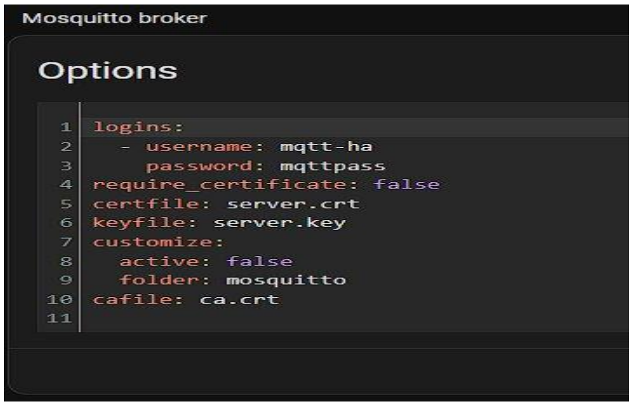
Vulnerability Analysis: In a real-world exploitation scenario, an attacker within the range of the smart home network could deploy a Wi-Fi dongle in monitoring mode to capture MQTT traffic. With tools like Wireshark, they could easily extract credentials and other sensitive information and gain control over the smart home system.

MQTT Encryption and Mitigation Approach

After identifying the significant vulnerabilities associated with unencrypted MQTT communication through Wireshark analysis, it became imperative to implement some security measures. We decided encrypting the MQTT traffic using TLS (Transport Layer Security).

TLS Setup: TLS (Transport Layer Security) is a cryptographic protocol designed to provide secure communication over a computer network. It ensures that data transmitted between devices is encrypted, preventing eavesdropping, tampering, and message forgery. The first step in securing the MQTT broker (Mosquitto) hosted on the Raspberry Pi 4 involved configuring it to support TLS encryption. This process required generating self-signed TLS certificates that would be used to encrypt the communication between the broker and its clients (the ESP32 module).

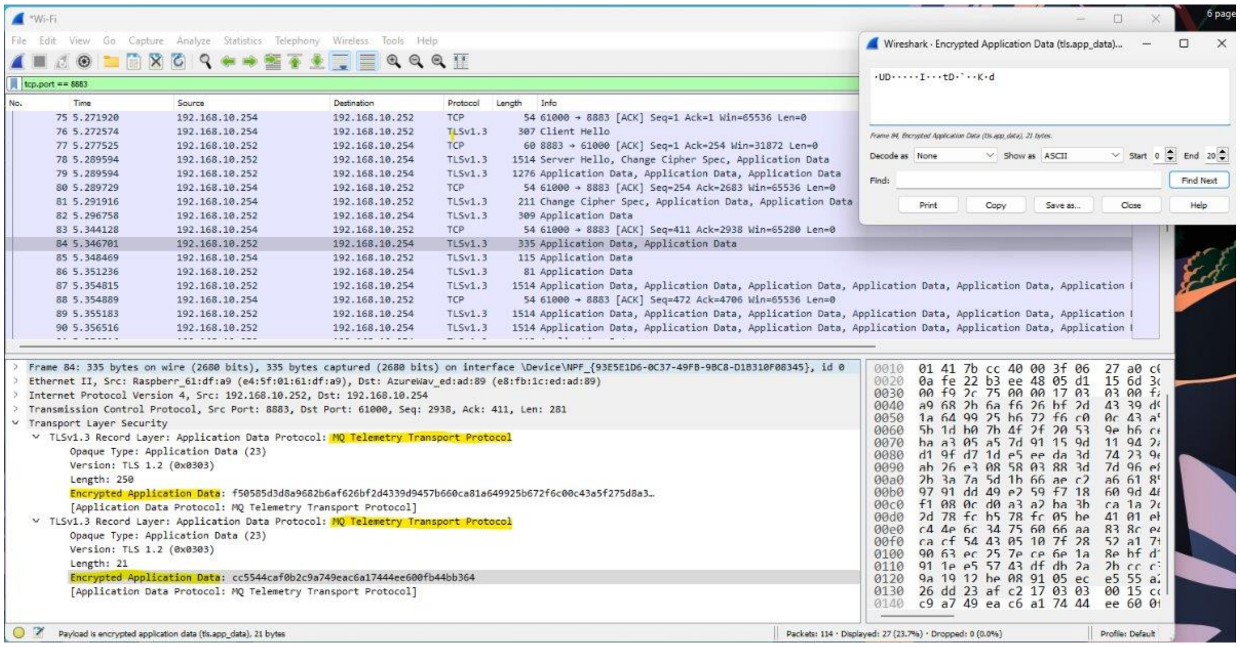
Certificate Generation: A self-signed certificate was created within the Home assistant. This certificate along with a private key was then installed on the Mosquitto broker to enable encrypted connections. The ESP32 module, as the client, was also configured to match the hash value of the certificate. This involved updating the client code to establish a secure connection with the MQTT broker using the generated certificates. The client now verifies the broker's identity before establishing a connection by ensuring that communication is only possible with a trusted broker.



```
logins:
  - username: mqtt-ha
    password: mqttpass
require_certificate: false
certfile: server.crt
keyfile: server.key
customize:
  active: false
  folder: mosquitto
cafile: ca.crt
```

Figure 13: Broker Config for certificate

Securing MQTT Messages: Once TLS was enabled, all MQTT messages exchanged between the broker and clients were automatically encrypted. This includes sensitive information such as usernames, passwords, and the actual payload data (e.g., sensor readings, commands). With TLS encryption, even if an attacker were to capture MQTT packets using Wireshark, the data would appear as masked due to the encryption. The attacker would be unable to decipher the contents without the appropriate decryption keys.



```
tcp.port == 8883

No.   Time       Source           Destination      Protocol  Length  Info
   75 5.271920   192.168.10.254   192.168.10.252   TCP          54 61000 → 8883 [ACK] Seq=1 Ack=1 Win=65536 Len=0
   76 5.272574   192.168.10.254   192.168.10.252   TLSv1.3     307 Client Hello
   77 5.277525   192.168.10.252   192.168.10.254   TCP          60 8883 → 61000 [ACK] Seq=1 Ack=254 Win=31872 Len=0
   78 5.289594   192.168.10.252   192.168.10.254   TLSv1.3    1514 Server Hello, Change Cipher Spec, Application Data
   79 5.289594   192.168.10.252   192.168.10.254   TLSv1.3    1276 Application Data, Application Data, Application Data
   80 5.289729   192.168.10.254   192.168.10.252   TCP          54 61000 → 8883 [ACK] Seq=254 Ack=2683 Win=65536 Len=0
   81 5.291916   192.168.10.254   192.168.10.252   TLSv1.3     211 Change Cipher Spec, Application Data, Application Data
   82 5.296758   192.168.10.252   192.168.10.254   TLSv1.3     309 Application Data
   83 5.344128   192.168.10.254   192.168.10.252   TCP          54 61000 → 8883 [ACK] Seq=411 Ack=2938 Win=65280 Len=0
   84 5.346701   192.168.10.252   192.168.10.254   TLSv1.3     335 Application Data, Application Data
   85 5.348469   192.168.10.254   192.168.10.252   TLSv1.3     115 Application Data
   86 5.351236   192.168.10.252   192.168.10.254   TLSv1.3      81 Application Data
   87 5.354815   192.168.10.252   192.168.10.254   TLSv1.3    1514 Application Data, Application Data, Application Data, Application Data, Application Data, Application
   88 5.354889   192.168.10.254   192.168.10.252   TCP          54 61000 → 8883 [ACK] Seq=472 Ack=4706 Win=65536 Len=0
   89 5.355183   192.168.10.252   192.168.10.254   TLSv1.3    1514 Application Data, Application Data, Application Data, Application Data, Application Data, Application
   90 5.356516   192.168.10.252   192.168.10.254   TLSv1.3    1514 Application Data, Application Data, Application Data, Application Data, Application Data, Application

> Frame 84: 335 bytes on wire (2680 bits), 335 bytes captured (2680 bits) on interface \Device\NPF_{93E5E1D6-0C37-49FB-9BC8-D1B310F08345}, id 0
> Ethernet II, Src: Raspberr_61:df:a9 (e4:5f:01:61:df:a9), Dst: AzureWav_ed:ad:89 (e8:fb:1c:ed:ad:89)
> Internet Protocol Version 4, Src: 192.168.10.252, Dst: 192.168.10.254
> Transmission Control Protocol, Src Port: 8883, Dst Port: 61000, Seq: 2938, Ack: 411, Len: 281
v Transport Layer Security
  v TLSv1.3 Record Layer: Application Data Protocol: MQ Telemetry Transport Protocol
      Opaque Type: Application Data (23)
      Version: TLS 1.2 (0x0303)
      Length: 250
      Encrypted Application Data: f50585d3d8a9682b6af626bf2d4339d9457b660ca81a649925b672f6c00c43a5f275d8a3…
      [Application Data Protocol: MQ Telemetry Transport Protocol]
  v TLSv1.3 Record Layer: Application Data Protocol: MQ Telemetry Transport Protocol
      Opaque Type: Application Data (23)
      Version: TLS 1.2 (0x0303)
      Length: 21
      Encrypted Application Data: cc5544caf0b2c9a749eac6a17444ee600fb44bb364
      [Application Data Protocol: MQ Telemetry Transport Protocol]

0010  01 41 7b cc 40 00 3f 06  27 a0 c
0020  0a fe 22 b3 ee 48 05 d1  15 6d 3
0030  00 f9 2c 75 00 00 17 03  03 00 f
0040  a9 68 2b 6a f6 26 bf 2d  43 39 d
0050  1a 64 99 25 b6 72 f6 c0  0c 43 a
0060  5b 1d b0 7b 4f 2f 20 53  9e b6 c
0070  ba a3 05 a5 7d 91 15 9d  11 94 2
0080  d1 9f d7 1d e5 ee da 3d  74 23 9
0090  ab 26 e3 08 58 03 88 3d  7d 96 e
00a0  2b 3a 7a 5d 1b 66 ae c2  a6 61 8
00b0  97 91 dd 49 e2 59 f7 18  60 9d 4
00c0  f1 08 0c d0 a3 a2 ba 3b  ca 1a 2
00d0  2d 78 fc b5 78 fc 05 be  41 01 e
00e0  c4 4e 6c 34 75 60 66 aa  83 8c e
00f0  ca cf 54 43 05 10 7f 28  52 a1 7
0100  90 63 ec 25 7e ce 6e 1a  8e bf d
0110  91 1e e5 57 43 df db 2a  2b cc c
0120  9a 19 12 be 08 91 05 ec  e5 55 a
0130  26 dd 23 af c2 17 03 03  00 15 c
0140  c9 a7 49 ea c6 a1 74 44  ee 60 0

Payload is encrypted application data (tls.app_data), 21 bytes
Packets: 114 · Displayed: 27 (23.7%) · Dropped: 0 (0.0%)
Profile: Default

Wireshark · Encrypted Application Data (tls.app_data)...
·UD·····I···tD·`··K·d
Frame 84, Encrypted Application Data (tls.app_data), 21 bytes.
Decode as: None   Show as: ASCII   Start: 0   End: 20
```

Figure 14: Post encryption packet capture

Testing and Validation

Post-Encryption Capture: After implementing TLS encryption, another packet capture and analysis was conducted using Wireshark. This was done to validate that the previously identified vulnerabilities had been effectively mitigated.

Encrypted Packets: The captured MQTT packets now showed that the data was encrypted. Instead of clear text, the payloads and credentials appeared as an incomprehensible string of characters.

The validation process confirmed that TLS encryption effectively addressed the vulnerabilities. The MQTT messages including login credentials and other sensitive data were no longer visible in clear text. The encryption not only protected the data but also ensured that the overall system functionality remained intact. The smart home system continued to operate smoothly, with all automation and communication processes unaffected by the added layer of security.

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