IRELE

Mobile and wireless network

Project report

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Contents

1 Introduction and concept

1.1 Device

The prototype is built around two ESP32 DevKit boards and two laptops running the MQTT broker and visualization tools. The goal is to monitor thermal conditions remotely with a robust encryption system

Hardware components

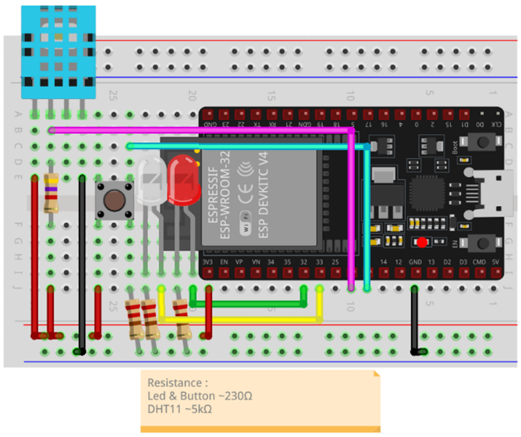


Figure 1.1: ESP32 schematic

- **Publisher ESP32** This board collects the environmental data in the room under test. And It sends the information to the MQTT server with encryption. It is connected to:
  - a DHT11 temperature and humidity sensor,
  - a push button used later for entering the Morse code,
  - two LEDs that provide simple feedback about the system state (Wi-Fi/MQTT connection, data transmission).

- **Subscriber ESP32** This second board plays the role of a remote command center. It receives the encrypted measurements from the MQTT broker, verifies the integrity and authenticity of the messages, and decrypts the payload. The same board also runs a small web server that exposes the current temperature and humidity to any device on the local network.
- **Computers running the MQTT broker** Laptops are used to host the Mosquitto MQTT brokers. Both ESP32 boards connect to this broker over Wi-Fi through a local access point (a smartphone hotspot in our case). The computer can also run additional tools for data visualisation, such as an MQTT dashboard or plotting software.

Roles of the devices

The **Publisher ESP32** works as a sensor node installed in the room. It periodically reads the DHT11 sensor, builds a JSON payload, encrypts this payload and sends it to the MQTT broker. The **Subscriber ESP32** works as the monitored unit of the room. It subscribes to the encrypted topics, checks the HMAC, detects replay attacks using a counter, decrypts the data and republishes a plain version for visualisation. In this way the security mechanisms can be tested without modifying the MQTT broker itself.

1.2 Concept

The project implements a secure remote monitoring system for temperature and humidity, using two ESP32 microcontrollers communicating over MQTT. One ESP32 acts as a Publisher, located in the environment to be monitored. It collects data from a DHT11 sensor, encrypts the measurements, and transmits them to an MQTT broker. The second ESP32 acts as a Subscriber. It receives the encrypted data, authenticates the source, decrypts the payload, and displays the information via a local web server and a visualization dashboard.

To ensure the security of the communication in an open wireless environment, the system implements a multi-layered security scheme. Maximizing confidentiality is achieved by ensuring data cannot be read by unauthorized parties using AES-128 encryption. We maintain integrity and authentication by verifying that data has not been tampered with and originates from the legitimate publisher using HMAC-SHA256. Repudiation protection ensures a definitive record of sequential messages by tracking a monotonically increasing sequence counter. For key agreement, we use Morse code, to derive session keys, which avoids the vulnerability of having hardcoded keys in the firmware source code. Finally, network obfuscation is implemented through a port knocking sequence to complicate traffic analysis.

2 Threat Model

2.1 Data flow diagram

In the first chapter, we discussed about the project concept where one ESP32 is used as a data publisher mimicking the data collection of a room we would like the thermal conditions to be controlled via a command center, which is the alias for our second ESP32.
The acquised data are sent from our ESP32 "publisher" to a MQTT server, installed on our machine for the example. The second ESP32 is subscribed to the MQTT server, receiving the published data and in charge of monitoring - controlling the room conditions. Those data are displayed on another MQTT server able to plot data evolution. **Speak about TCP protocol ? - first handshake**
The data flow is shown on the figure 2.1

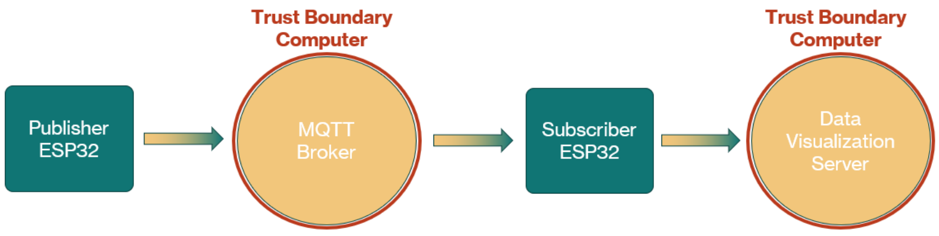


Figure 2.1: Data flow diagram

For completeness, we will consider our data as highly sensitive - with strict security needs - where the room thermal regulation cannot be vulnerable to seizing control attacks or unstablizing temperature attacks for example.
We would therefore need to mitigate all types of attack by integrating a security strategy considering the ressources constraints dependent on the hardware used - in our case, the ESP32 devkit with :

1. 4MB flash memory

2. 520KB RAM

3. Dual-core 32-bit processor

Thus HTTPS / TLS protocol are not adapted for our devices and key cryptoghraphy containing complex mathematical operation like RSA cannot be implemented. This suitable security strategy counter acting the whole span of threats while fitting into the hardware and meeting the decyphering process speed will be discussed in the last chapter namely the "Security mitigation".

Before treating about the security strategy, we would need to identify the security threats our model needs to deal with. The STRIDE model will be used in this perspective in the next section.

Figure 2.2

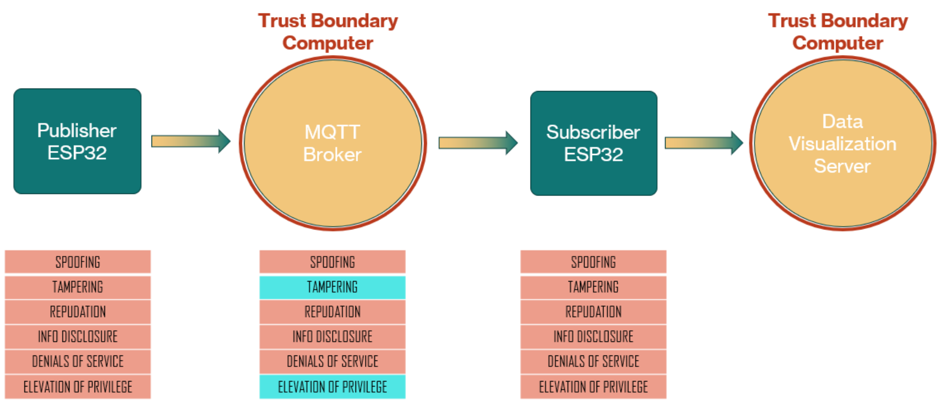


Figure 2.2: STRIDE model verification for project data flow

2.2 STRIDE Threat Model

The STRIDE threat model is an approach used to identify and categorize potential security threats and vulnerabilities in software systems. Developed by Microsoft, the acronym STRIDE represents six main categories of threats. These figures below illustrate all categories, their description and how they are mitigated in the project.

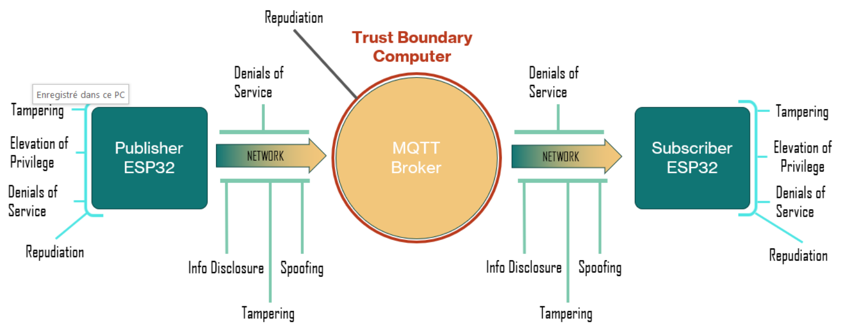


Figure 2.3: STRIDE model and threats localization

STRIDE Category	**Threat Description**	**Attacked Component/Data Flow**	**Security Mitigation (Protocol)**
Spoofing (Authentication)	An attacker impersonates a legitimate ESP32 device or the MQTT Server to inject false data or commands.	ESP32 ↔ Server Communication	**Authentication** using a **Message Authentication Code (MAC)**, such as HMAC-SHA256, to verify the sender's identity with a shared secret key derived from PBKDF2.
Tampering (Integrity)	Data (sensor readings) is intercepted and modified while in transit over the network.	Sensor Data → Server, Control Commands	**Integrity** enforced by the MAC (HMAC-SHA256). The receiver recalculates and compares the MAC to detect any alteration.
Information Disclosure (Confidentiality)	An attacker eavesdrops on the network and reads sensitive data (Temperature,Humidity...).	All Communication over the Network	**Encryption** of the MQTT payload using AES-128. An additional layer is provided by Port Knocking to make sniffing and channel monitoring harder.
Denial of Service (DoS)	An attacker floods the ESP32 or MQTT server with excessive traffic or requests, consuming resources.	ESP32 or Server Resources	**Rate-limiting** controls on the MQTT broker (assumption) and the use of Port Knocking to obscure the communication channel, reducing the window for targeted attacks.
Repudiation (Non-Repudiation)	A legitimate device or the server denies having sent a critical or malicious message.	All Communication	The HMAC proves the message's origin from the authentic sender, and the counter ensures a definitive record of sequential messages, preventing the sender from denying transmission.
Elevation of Privilege (Authorization)	A compromised device gains access to MQTT topics or capabilities it should not have permission for.	ESP32 ↔ Server Communication, MQTT Topic Subscriptions	Strict Authorization controls on the MQTT broker (assumption) and the requirement to correctly decrypt the secret key via the Morse code sequence before publishing data.

Table 2.1: STRIDE Threat Model and Security Mitigations for ESP32-MQTT Setup

3 Security Mitigation

Discuss about

1. Hardware being crypted (assumption)
2. Key being encrypted with usage of morse code through PBDKF2 (Additional feature !!) and saved in flash
3. Decryption of the key with morse code before sending payload to get back the plain key
4. Encryption of paylaod with AES-128 bits encryption (low ressources demand)
5. Data sent to MQTT server (assumed to have a secured hardware and files secured too in the OS)
6. HMAC generation for ensuring authentification (at MQTT server - assumption) at the surbscriber
7. Replay detection verification with counter (at MQTT server - assumption) at the surbscriber
8. Port knocking implementation to complexify the sniffing (changing port)

3.1 Security scheme

The security scheme is designed to protect the IoT communication channel against information disclosure, tampering, and repudiation. We implemented an application-layer security protocol that ensures data privacy and integrity before it even reaches the network stack.

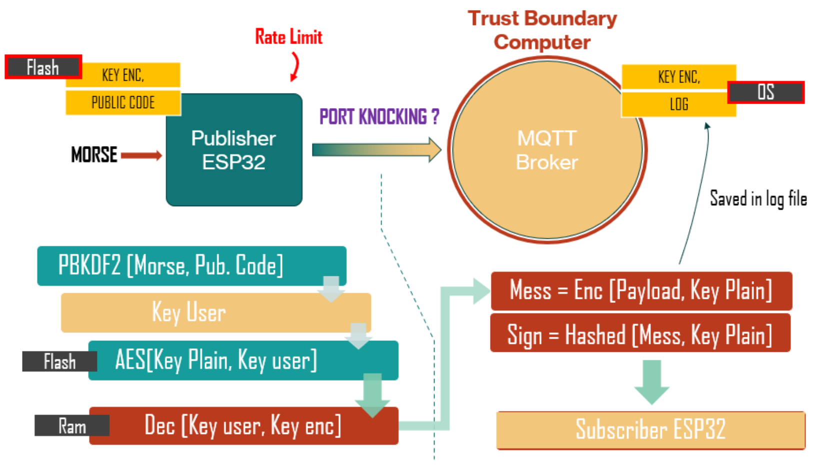


Figure 3.1: Security strategy integration in the project data flow

Key Generation and Management

To avoid storing the master encryption key in plaintext within the source code or the flash memory, the system uses a password-based key derivation function. At startup, the user manually inputs a secret password using a push-button interpreted as Morse code. This password is then passed through the PBKDF2 algorithm using HMAC-SHA256 to derive a session key. The actual encryption key, which is stored in the non-volatile storage in an encrypted form, is then decrypted using this session key. The decrypted key is stored only in RAM and used for the duration of the session.

Encryption and Confidentiality

The sensor data, including temperature and humidity, is formatted into a JSON structure. This payload is then encrypted using AES-128. For each message, a fresh Initialization Vector is randomly generated to ensure that the same data results in different ciphertexts every time. The payload is then encrypted using the session key derived during the startup phase.

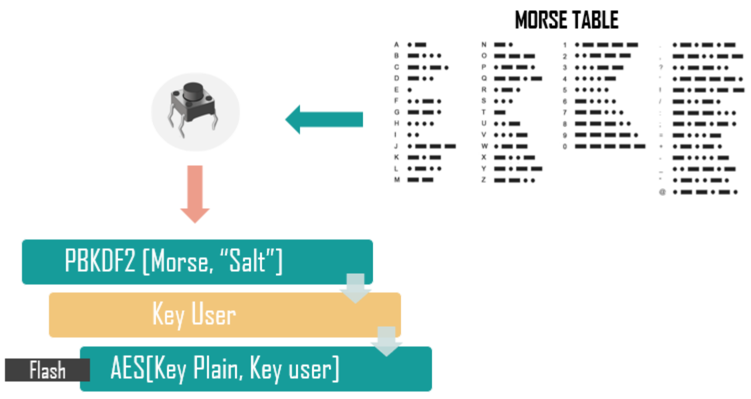


Figure 3.2: Encrypted key generation

Authentication verification and Integrity

To ensure the authenticity and integrity of the message, an HMAC-SHA256 signature is generated. The final message payload includes the IV, a sequence counter, and the encrypted data. An HMAC-SHA256 signature is calculated over this entire message using the session key. The message and its corresponding signature are published to separate MQTT topics.

Repudiation Protection

A monotonic counter is maintained by the publisher and stored in non-volatile memory to survive reboots. The counter is incremented for every sent message and embedded in the payload. Since the counter is part of the data covered by the HMAC, it cannot be tampered with. The subscriber tracks the last received counter value. Any received message with a counter lower than or equal to the last valid counter is rejected to ensure non-repudiation.

Network Defense via Port Knocking

As an additional layer of obfuscation, the system implements a synchronized port rotation mechanism. Both the publisher and subscriber cycle through a predefined sequence of MQTT broker ports. After a successful transmission, both devices switch to the next port in the sequence, making continuous passive sniffing more difficult for an attacker listening on a single port.

3.2 Results

In thi section, we will review the results obtained during the implementation of the thermal regulation concept - previously discussed - with two ESP32 communicating through a MQTT server in a fully securised environment (authentification, confidentiality and integrity).

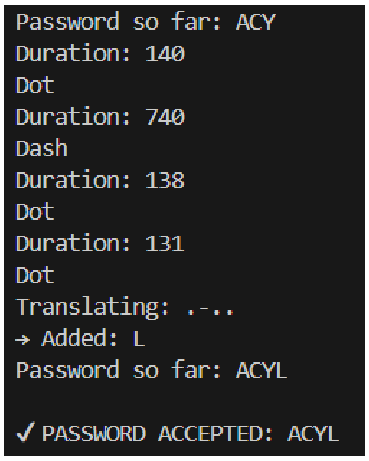
We will proceed step by step by confirming the implementation of :

1. The morse code acquisition with debouncing function for security
2. PBKDF2 key generation and decryption of the encrypted key in the flash memory
3. Encryption of the payload with the decrypted key
4. Decryption of the payload at the subscriber
5. Replay detection verification
6. Port knocking verification

3.2.1 Morse Code

The morse code acquisition passes by the implementation of a look-up table translated unique succession of **dots** and **dashes** to an alphabetic letter. These **dots** and **dashes** being generated depending on the duration when the push button has been pressed. Just to ensure the translation code was correctly implemented, the code compares the morse code encoded and the one we should use to decrypt the key stored in the flash. Of course, this verification is not done in practice as it would mean the morse code is stored in the flash memory which could be an additional break in our security strategy - morse code is supposed to be kept secret and shared verbally.

Figure 3.3 shows the results of the last letter encoding (and the the verification of the morse code).



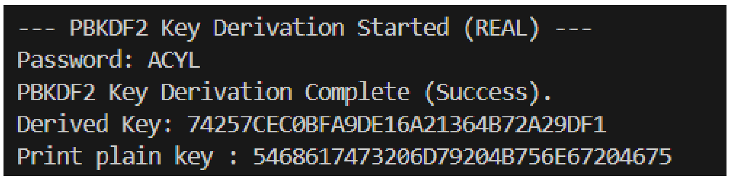
```
Password so far: ACY
Duration: 140
Dot
Duration: 740
Dash
Duration: 138
Dot
Duration: 131
Dot
Translating: .-..
→ Added: L
Password so far: ACYL

✓ PASSWORD ACCEPTED: ACYL
```

Figure 3.3: Morse code implementation Result

3.2.2 PBKDF2 encryption

The following security phase is the decryption of the encrypted key saved in the non-volatile memory through the PBKDF2 encryption and AES decryption. The figure 3.4 shows the following results :

1. Morse code encoded with the push button
2. Derived 16-bytes key generated by the PBKDF2 algorithm (Morse, "Salt", HMAC 256, 1000 iterations)
3. Encrypted 32-bytes key saved in the flash - $\text{Key}_{\text{enc}} = \text{AES}(\text{IV code}, \text{Key}_{\text{plain}})$
4. Decryption of the key - $\text{Key}_{\text{plain}} = \text{Dec}(\text{IV code}, \text{Key}_{\text{enc}})$
5. $\text{Key}_{\text{plain}} = 0x54, 0x68, 0x61, 0x74, 0x73, 0x20, 0x6d, 0x79, 0x20, 0x4b, 0x75, 0x6e, 0x67, 0x20, 0x46, 0x75$ - **Thats my Kung Fu** in 16 ASCII



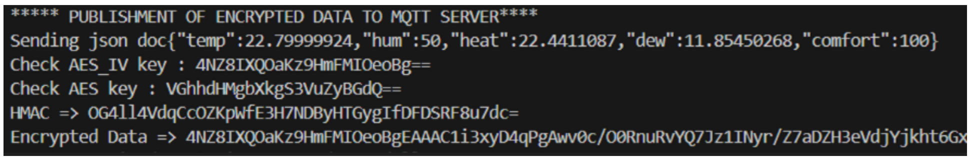
```
--- PBKDF2 Key Derivation Started (REAL) ---
Password: ACYL
PBKDF2 Key Derivation Complete (Success).
Derived Key: 74257CEC0BFA9DE16A21364B72A29DF1
Print plain key : 5468617473206D79204B756E67204675
```

Figure 3.4: PBKDRF2 encryption verification

3.2.3 Encrypted data publishment

Once the plain key ($\text{Key}_{\text{plain}}$) has been generated, the thermal data can be encrypted with AES-128 bits encryption. The figure 3.5 shows the details fo the encryption functionality and the results of the encrypted payload.

1. Thermal conditions gathered in a java script object notation (readable text to send structured data)
2. IV and plain key shown for transparency in **Arduino String**
3. Hmac and cypher payload generation with AES-128 bits encryption.
4. Publishment of the data on the MQTT server after client connexion on MQTT server on dedicated port.



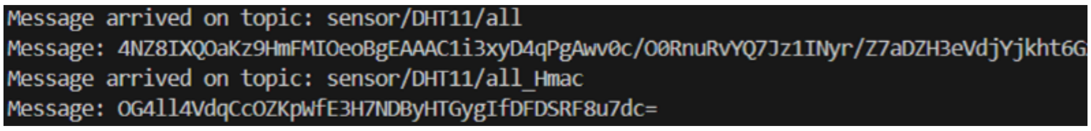
```
***** PUBLISHMENT OF ENCRYPTED DATA TO MQTT SERVER****
Sending json doc{"temp":22.79999924,"hum":50,"heat":22.4411087,"dew":11.85450268,"comfort":100}
Check AES_IV key : 4NZ8IXQOaKz9HmFMIOeoBg==
Check AES key : VGhhdHMgbXkgS3VuZyBGdQ==
HMAC => OG4ll4VdqCcOZKpWfE3H7NDByHTGygIfDFDSRF8u7dc=
Encrypted Data => 4NZ8IXQOaKz9HmFMIOeoBgEAAAC1i3xyD4qPgAwv0c/O0RnuRvYQ7Jz1INyr/Z7aDZH3eVdjYjkht6Gx
```

Figure 3.5: Encrypted data publishment on MQTT server

3.2.4 Decryption at the subscriber

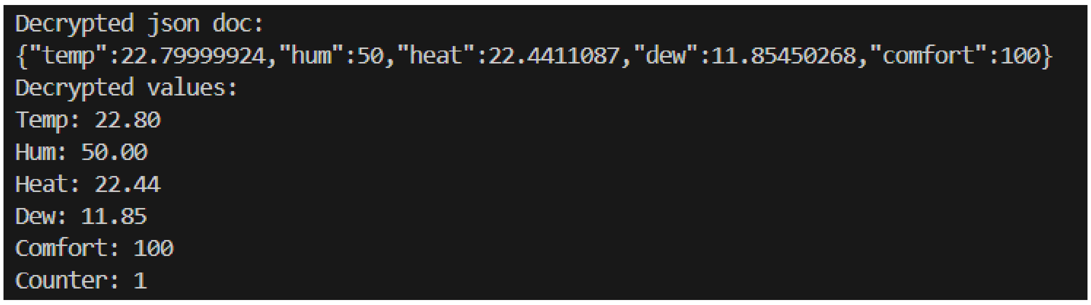
The second ESP32 subscribed to the same MQTT server - listening to the same port as the publisher - receives the cypher message containing HMAC signature and encrypted payload. From the inverse encryption process, the cypher is decrypted and the result details are shown in the figure 3.6 and 3.7.

1. Encrypted message and HMAC signature sent to the subscriber
2. Payload decrypted with the plain key (decrypted at the subscriber with the same secret morse code)
3. Display of the counter countering replay attacks.



```
Message arrived on topic: sensor/DHT11/all
Message: 4NZ8IXQOaKz9HmFMIOeoBgEAAAC1i3xyD4qPgAwv0c/O0RnuRvYQ7Jz1INyr/Z7aDZH3eVdjYjkht6G
Message arrived on topic: sensor/DHT11/all_Hmac
Message: OG4l14VdqCcOZKpWfE3H7NDByHTGygIfDFDSRF8u7dc=
```

Figure 3.6: Subscription to MQTT server topics



```
Decrypted json doc:
{"temp":22.79999924,"hum":50,"heat":22.4411087,"dew":11.85450268,"comfort":100}
Decrypted values:
Temp: 22.80
Hum: 50.00
Heat: 22.44
Dew: 11.85
Comfort: 100
Counter: 1
```

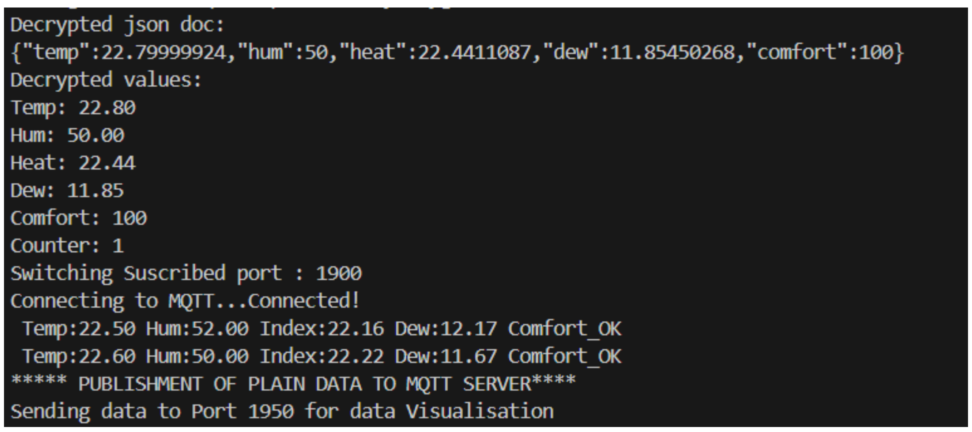
Figure 3.7: Decryption verification

3.2.5 Port Knocking

To complete the results section, the terminal shows the results got during data sending experiment from the subscriber side.

One can observe that the port is switching once the packet has been received - **Switching Subscribed port : 1900**. This port switch simulates a synchronised port switching between the publisher - MQTT server and the subscriber.

Figure 3.8



```
Decrypted json doc:
{"temp":22.79999924,"hum":50,"heat":22.4411087,"dew":11.85450268,"comfort":100}
Decrypted values:
Temp: 22.80
Hum: 50.00
Heat: 22.44
Dew: 11.85
Comfort: 100
Counter: 1
Switching Suscribed port : 1900
Connecting to MQTT...Connected!
 Temp:22.50 Hum:52.00 Index:22.16 Dew:12.17 Comfort_OK
 Temp:22.60 Hum:50.00 Index:22.22 Dew:11.67 Comfort_OK
***** PUBLISHMENT OF PLAIN DATA TO MQTT SERVER****
Sending data to Port 1950 for data Visualisation
```

Figure 3.8: Port switching for sniffing security improvement

3.3 Discussion

Discuss about :

1. the assumption the MQTT server and the ESP32 flashs were secured - hardware level - trust zone area !
2. That the port knocking can work only if the server switches from one listening port to another listening port in synchronization with the ESP32
3. Explain that attacks like low-level instructions counting can be used to understand the encryption we used (last year course with Tobias)?
4. Explain the maybe AES 128-bits encryption is a bit light for sensitive data ? I do not know but maybe be good to check

In this section, we discuss the security assumptions and the remaining limitations of our implementation.

Hardware trust assumptions

In our design, we "assume" that the MQTT broker runs on a trusted computer and that the ESP32 flash memory is protected at the hardware level. Under this assumption, the attackers can observe and modify the wireless traffic, but they cannot directly read or overwrite the keys stored in flash or the files of the MQTT server.

If this assumption is violated (for instance, if an attacker obtains physical access to the board and can dump the flash contents), our scheme would not be sufficient: the long–term AES key and the PBKDF2 parameters could be extracted, and all traffic could be decrypted offline.

Port knocking and synchronisation

As an additional defence in depth, we implemented a form of *port knocking* on the ESP32 side. Instead of always sending encrypted MQTT traffic to a single fixed port, the publisher and subscriber cycle through a predefined list of ports (1883 → 1900 → 1925 → 1960 → ...). After each encrypted payload is sent and acknowledged, both ESP32 devices update an internal index and reconnect to the broker using the next port in the sequence. This makes passive sniffing slightly more difficult, because an attacker cannot simply capture all traffic by listening on a single port.

In a *strict* port-knocking design, the MQTT broker would enforce the same sequence: the server would initially keep all application ports closed and only open the next port in the list after a correct "knock" on the current one. Such behaviour requires the synchronisation between the client and the server. If the broker does not follow the same sequence, an attacker who listens on all open ports can still observe every packet.

In our implementation the Mosquitto broker is configured to listen on all ports of the sequence at the same time, without enforcing any ordering. As a consequence, our port-switching mechanism should prevent from a naive sniffing. A possible improvement for future work would be to move the port-knocking logic to the server side so that only the correct sequence of ports is accepted and all other connection attempts are rejected.7

Side–channel leakage

The implemented counter-measures mainly address network-level threats such as spoofing, tampering and replay. On a small micro-controller there are additional side-channel attacks: an attacker could measure execution time, count low-level instructions or observe power consumption in order to recover information about the AES key.

Protecting against these attacks is outside the scope of this work. In practice, defending against side channels would require constant-time cryptographic implementations and specific hardware counter-measures, which are not provided in our prototype.

Security level of AES-128

The payload is encrypted with AES in CBC mode with a 128-bit key. From a purely cryptographic point of view, AES-128 is still considered secure for most applications and no practical attack is known that breaks the algorithm with a realistic amount of resources.

However, for highly sensitive data and long-term confidentiality, standards often recommend larger keys (e.g. AES-256) and additional protections such as key rotation. In our project the main limitations are therefore not the theoretical strength of AES-128 itself but the way keys are stored, derived and handled on low-cost IoT hardware.

3.4 Conclusion

4 Conclusion

This project successfully developed and implemented a functional and highly secure Internet of Things (IoT) setup using two ESP32 microcontrollers communicating via an MQTT broker. We met all core requirements, including reading sensor data (temperature and humidity), enabling push-button control, and facilitating data exchange with a centralized server. On top of the core requirements we add some features while implementing the setup: room comfort estimation, morse password to start the communication, counters to mark each payload and an external server to publish the data.
We successfully achieved the required security properties and we added some other contributions:

- Confidentiality: Achieved by encrypting the entire data payload using AES.
- Integrity and Authentication: Ensured through the use of an HMAC signature generated from a secret key and verified by the recipient.
- Our contribution to secure key storage involved deriving the key through PBKDF2 using a secret Morse Code input from the push button. This added a crucial layer of physical security and user-based authentication for the initial key decryption.

Future Work

- Implementing true hardware-level security, such as leveraging the ESP32's Flash Encryption features to ensure that stored key cannot be read at all.
- Implement Port knocking with the MQTT server such that during the transmission of one packet the MQTT reads only the designated port.