

BUCHAREST UNIVERSITY OF ECONOMIC STUDIES

Cybernetics, Statistics and Economics Informatics Faculty

Department of Economics Informatics

**DISSERTATION**

Scientific Coordinator

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Graduate

Andrei-Robert CAZACU

Bucharest

2022

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Secure IoT solution for office building monitoring

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# **INTRODUCTION**

Despite IoT being in the spotlight for several years now, Gartner still predicts a five time increase in number of devices from 2018 to 2028 [1], up to 1.9 billion units, which further intensifies the need for security among IoT nodes. Through the years, a significant amount of effort has been spent standardizing and improving inter-operability among devices, spawning several lightweight application layer protocols such as CoAP [2], standard formats for data during transit such as IPSO objects [3], or means to encode data that further reduces the size of the payload such as CBOR [4]. While Internet of Things wasn’t officially a concept until 1999, one of the first examples of such a device surfaced in the early 1980s, an internet connected Coca Cola vending machine placed at the Carnegie Mellon University which local programmers modified to report whether a drink was available, and if it was cold or not before making the trip [5]. The phrase “Internet of Things” was coined by Kevin Ashton, then Executive Director of Auto-ID Labs, during a presentation he made for Procter & Gamble.

Recently, great efforts have been poured into securing IoT devices, empowered by the rapid advancements in technology which allows complex cryptographic operations to be executed on device in a reasonable amount of time. While solutions based on existing cryptographic algorithms have recently surfaced, such as Connectivity Standards Alliance’s Matter [6], which relies on the Public Key Infrastructure model, new lightweight cryptographic algorithms are being developed in an attempt to make security a thing for even the smallest of devices. This pursuit is fuelled by NIST which initiated a process to solicit, evaluate, and standardize lightweight cryptographic algorithms in August 2018 [7].

The purpose of this paper is to combine existing and emerging technologies into a polished IoT product that can be used for office building monitoring, but still be expandable to suit other needs such as smart cities, or smart homes. This modularity is baked into the architecture of the product, making no assumption about the type of the data sent or received, nor about the type of sensors attached to the node. Another imposed constraint was developing a security model that would be able to ensure the confidentiality of the payload without requiring a gateway, leading to greater computational effort that has to be placed upon the IoT node, with the benefit of being able to push the data directly into the cloud and having almost zero configuration needed. While this architecture may not confine to previously agreed standards of having several nodes connected via Intranet to a gateway which then pushed data into a public or private cloud, big names in the cloud computing industry such as Amazon Web Services, Microsoft Azure and Oracle have started shipping solutions that cater to such kind of cloud connected nodes. Solutions have also appeared in the hobbyist market, such as Arduino Cloud, which shows the industry wide trend of IoT edge computing and edge AI.

For clarity, this dissertation has been structured into four chapters:

1. Introduction
2. Technical and Mathematical Concepts, where concepts fundamental to this dissertation are discussed
3. Proposed solution, where the architecture and the implementation are discussed
4. Conclusions, a chapter which discusses the pros and cons of the designed solution

# **TECHNICAL AND MATHEMATICAL CONCEPTS**

## **2. 1. What is Internet of Things?**

## **2. 2. Cryptography**

## **2. 3. Blockchain**

## **2. 4. MQTT**

## **2. 5. CoAP**

## **2. 6. Cloud computing**

## **2. 7. Machine Learning**

# **PROPOSED SOLUTION**

## **3.** **1. High Level Solution Description**

A single IoT node was built as a proof of concept to demonstrate the feasibility and power of the solution.

The node features an ESP32 which has several sensors attached to it, such as DTH11 temperature and humidity sensor, SW-420 vibration sensor, and MQ-2 gas sensor. While this may not provide an exhaustive list of sensors that can be attached to the node, it serves the purpose of demonstrating the flexibility with which the architecture handles different types of data.

Before pushing any data to the cloud, the device needs to have the Wi-Fi connection configured, but also to have its identity attested by the attestation server. This is done by using public key cryptography. At manufacture time, three files are burnt into the flash storage of the device: the root certificate and device certificate which has both a public and a private key. Impersonation of the device is avoided by encrypting the flash storage before shipping the device to the end-user, making the key uncompromisable. This is done by leveraging a built-in feature of the ESP32 which transparently handles encryption and decryption of data on the fly, saving the used AES key in eFUSE [8].

Following the attestation of the node, a symmetric key has been established which will then be burnt into the encrypted flash storage for use the next time the node will be restarted. The integrity of the key is assured by using Elliptic Curve Digital Signature Algorithm (ECDSA), signed with the device’s own private key. This key will expire each 24 hours, which ensures forward secrecy if the key is compromised. Following the expiration of the key, it will be removed from non-volatile storage alongside its signature, and the node restarted to perform the attestation process again.

The symmetric key is used in establishing MQTT connection in TLS-PSK mode, which is less computationally expensive than TLS with public key cryptography. This means that the cost of establishing a key is incurred only once each 24 hours when attesting the origin of the device.

The payload will be CBOR encoded and formatted according to the IPSO guidelines and then sent to the MQTT broker in the cloud. From here, the possibilities for data manipulation are endless, enabling functional style programming, subscribing to each topic that is of interest and performing actions when data is received, or persisting the data in a relational or non-relational database for later use.

For this proof of concept, besides the previously stated components, a cloud hosted clustered MySQL setup will be used, enabling fast responses while creating no bottleneck for simultaneous data insertions and retrievals. Two microservices have been developed using the Spring Boot framework, one that subscribes to all the available topics of devices that have undergone the attestation process and persists the information into the database, and another one that performs queries which are exposed via a HTTP REST interface.

All requests are authenticated and authorized in a stateless manner using JSON Web Tokens. This permits scaling with ease, decoupling the login from the machine that first served the request.

## **3.** **2. Bill of Materials**

Table 1. Bill of materials

|  |  |  |  |
| --- | --- | --- | --- |
| COMPONENT | UNIT PRICE(LEI) | QUANTITY | TOTAL PRICE |
| ESP32 DEV BOARD | 42.99 | 1 | 42.99 |
| DTH11 TEMP AND HUMIDITY SENSOR | 11.99 | 1 | 11.99 |
| SW-420 VIBRATION SENSOR | 4.89 | 1 | 4.89 |
| MQ-2 GAS SENSOR | 12.49 | 1 | 12.49 |
| BATTERY PACK | 109.99 | 1 | 109.99 |
| TOTAL | 182.35 | | |

1. ESP32 Development Board

ESP32 is a series of low-powered system on a chip microcontrollers featuring Wi-Fi and Bluetooth, developed by Espressif Systems, a Shanghai-based Chinese company, and manufactured by TSMC using their 40nm node.

The particular flavour used here is ESP32S onto a ESP-WROOM-32 derived development board. This features a dual core Tensilica LX6 clocked at either 160 or 240MHz with a 32bit architecture, has an Ultra-Low Power coprocessor, 520KB of RAM and 4MB of flash storage that can be partitioned to the user’s preference. It also features Wi-Fi 802.11 b/g/n and Bluetooth 4.2 with BLE support.

This board is used as an IoT node and performs cryptographic operations, sensor reading and sends data over MQTT to the broker hosted in a cloud instance.

1. DTH11 Temperature and Humidity Sensor

DHT11 is a temperature and humidity sensor that output a digital signal on the data pin. Temperature is measured using a negative coefficient thermistor (NTC) and the relative humidity is measured using a capacitive sensor. The humidity sensing range can be between 20 and 90 % RH and its measurement accuracy is of +/- 5% RH. The temperature measurement range is from 0 to 60◦C and its accuracy is of +/- 2◦C. The supply voltage accepts ranges between 3.3V and 5V.

1. SW-420 Vibration Sensor

The vibration sensor used has a LM393 comparator and uses the SW-420 vibration sensor module that is normally closed, outputting a digital signal on the data pin. Under normal circumstances, the vibration switch is under closed conduction state, outputting digital low. Under strong vibrations, the sensor will output high. It has operating voltage ranging from 3.3V to 5V.

1. MQ-2 Gas Sensor

MQ-2 gas sensor is highly response and very sensitive, capable of detecting gases such as: butane, liquefied petroleum gas, propane, methane, alcohol, smoke, hydrogen, and other harmful gases.

It is based on a Metal Oxide Semiconductor type sensor, also known as chemiresistors, as the detection is based upon change of resistance of the sensing material when the gas meets the material. This sensor has an operating voltage of 5V.

1. Battery pack

The battery pack provides power to the IoT node, so it can be placed where there are no wall plugs.

## **3. 3. In-depth explanation of the solution**

For clarity, this solution can be split into two parts, the IoT node and the cloud applications.

Diagram

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Figure 3‑1. High Level Architecture Overview

The IoT node is composed of an ESP32 with several sensors connected to it using a breadboard. When designing the node, careful planning had to be done regarding the processing power, memory capacity and dimensions while still keeping the costs as low as possible in order to provide a marketable solution. While using a Raspberry Pi for example would have rendered faster processing times and easier development, the footprint of the node would be bigger, but the price would be the real deterrent, ballooning the cost at least 5 times. Since this is a price elastic market [9], such a device would need an attractive price in order to gain market traction.

For the perception layer of the solution, three sensors were used, the DTH11 temperature and humidity sensor, the SW-420 vibration sensor and MQ2 gas sensor. The ESP32 development board chosen features 30 GPIO pins, of which 18 Analog-to-Digital channels, 3 SPI interfaces, 3 UART interfaces, 2 I2C interfaces, 16 PWM output channels, 2 Digital-to-Analog, 2 I2S interfaces and 10 capacitive sensing GPIOs. According to the datasheet, 10 Analog-to-Digital channels due to Wi-Fi, but the solution’s requirements are still met. Power was used from both the 3.3V pin and the VIN which supplies 5V when connecting the sensors, although preferring the lower voltage when possible. When connecting the temperature and humidity sensor, a 10K Ω pull up resistor was connected on the data pin. This outputs digital signal, and as such was connected to the GPIO 4 pin. The SW-420 vibration sensor was also connected to the 3.3V power source and ground, while the data pin was connected to the GPIO 18 pin in digital mode. The MQ2 gas sensor is the only sensor that doesn’t work at 3.3V, while also requiring a burn in period of 24 to 72 hours in order to work correctly. This sensor outputs an analogue signal, and as such was connected to the GPIO 35 pin. Internally, this pin maps to the Analog-to-Digital converter ADC1, which is still available despite using Wi-Fi.

Diagram, schematic

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Figure 3‑2. Wiring Diagram

After wiring up the node and the sensors, another important decision had to be made regarding the development stack used. While the OS of the device is FreeRTOS, the manufacturer offers two possible abstractions on top: be it Arduino framework, or their own ESP-IDF (Espressif Integrated Development Framework). The difference is significant, Arduino offering an OOP paradigm along with a huge amount of community created libraries, while ESP-IDF is task oriented and has manufacturer developed libraries, along with a tight integration with the hardware and access to low level functions. The flip side is that both use a modified version of the GCC (GNU Compiler Collection), offering some level of portability. This proved to be very important, since back and forth movement was performed during the development process as issues arose.

The solution started as an Arduino project, but the security-sensitive aspect of the solution proved to be impossible to implement without the tight knit integration with the hardware of the ESP-IDF. This is due to the fact that the Arduino abstraction is shipped as a binary distribution, precompiled with the settings the Espressif deemed most relevant while not taking up unnecessary space in the non-volatile memory, while the ESP-IDF allows to build from source using a highly configurable architecture. The configurability is achieved by using a custom build system based partly on CMake, with compile time settings being altered by using the *menuconfig* [10]. This switch allowed free access to all hardware features, such as the transparent runtime encryption of flash memory needed in order to fill in the security puzzle, being able to ensure the confidentiality of the files stored in flash non-volatile memory. Another reason for the switch was the absence of the PSK option from the Arduino binaries, needed to smoothen the connection process to the broker. While this solved most of the issues, drawbacks were present such as the loss of important Arduino libraries that were used. While they were written in C++, and with enough effort any code can be built with any build system, dependencies of the Arduino framework were baked into every third-party library. Even though the dependencies could be removed, be it rewriting the third-party library or writing new code from scratch, time is of the essence, being one of the most valuable resources. This is where the flexibility of the ESP-IDF build system came into play, tying in the whole solution together, allowing the compiling of the Arduino sources and linkage with the other components. Each Arduino library still had to be integrated with the CMake based build system, but it required significantly less effort than writing the required functionality from scratch.

With the underlying technical stack detailed, attention can now be shifted to the functional part of the product. The core functionality of the solution is secure transmission of sensor data directly into the cloud, while still offering an easy to expand and pluggable architecture. Sensor data is handled transparently and collection of it is abstracted in such a manner that new sensor capabilities can be added with little to no effort. The pluggable aspect of the architecture is offered by the possibility to enable or disable optional features at runtime, such as running ML inference on the edge node using a pretrained neural network specialized in anomaly detection or sending blockchain transactions using the sensor data as parameter.

Diagram

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Figure 3‑3. Node initialization process

The initialization process of the node as seen in Figure 3-3 starts with the establishment of the Wi-Fi connection. At first boot, no credentials would have been stored inside the ESP32, at which point the node would switch from Wi-Fi station mode into Access Point mode, start an HTTP Server and wait for the user to enter the network credentials.

There is no application level security at this point, relying solely on the the ISO/OSI Layer 2 security offered by the network, since the access point is accessible only with a password.

The user is aided into inputting the correct network name by performing a scan of available networks and embedding that information before serving the HTML page to the browser. The Arduino library AsyncWebServer was used to create the HTTP server, with several modifications in order to be able to be built under ESP-IDF environment. The library is fully asynchronous, even supporting advanced features such as serving pages from the flash and template expansion of strings. The configuration page was created using HTML5 and Bootstrap, the credentials being sent using HTTP POST and persisted into the node. After setting the credentials, the node would restart and either proceed to the attestation process if the connection would be established successfully or switch back to Access Point mode and wait for new credentials to be inputted.

A picture containing graphical user interface

Description automatically generated Figure 3‑4. Sensor Configuration page

Following successful establishment of network connection, the attestation process is undergone, which is involves a multi-step flow involving complex cryptographic operations. The scope of this process is to attest the origin of the node, along with session key establishment used for connecting to the MQTT broker is TLS-PSK mode.

The process involves two parties, the IoT node and the attestation server, using plain HTTP as transport.

This process is initiated by the IoT node and is performing using plain HTTP. On the server side, a Java application was developed using the Spring Boot framework and a custom abstraction layer on top of Java Cryptography Architecture (JCA). Bouncy Castle was also added as a provider in order to supply the needed elliptic curve cryptography operations. On the node side, the HTTP Client provided as part of ESP32’s Arduino framework was used for issuing requests, while the cryptographic operations were supplied from a custom built library that uses mbedTLS. Making the JCA and mbedTLS work together deemed quite challenging, seeing as both have their own proprietary representation of keys and parameters. The response to this was unwrapping all the JCA abstraction and accessing the raw fields of the Bouncy Castle implementation in order to provide them in a manner that mbedTLS would accept. Being a library designed to be used in low-powered embedded environments, this often meant that the input is expected to be uncompressed and unencoded.

The attestation is commenced using HTTP Post to */clientHello* endpoint passing the device certificate encoded in Base64. The server then decodes the certificate and attempts to create an JCA object representation of it. If this step fails, the server will respond with HTTP status code 400, also known as bad request, and will halt the attestation process. Otherwise, the certificate is stored in a Hash-Map stored in volatile memory, with the key being the IP of the request. The storage is in-memory since cleaning of unused database records would be a processing intensive task in a high-volume environment, with the owned cost of increased memory consumption. As a response, the X and Y coordinates of the server’s public key will be sent, encoded in Base64. Besides this, the origin of the node can be attested by verifying the certificate’s signature, having the requirement to be signed by the same Certification Authority as the attestation server.

The second step of the attestation process is commenced by issuing a HTTP POST request to */keyExchange*. Elliptic Curve Diffie Hellman parameters are generated on the client side, with which the request body is constructed as the Base64 representation of the concatenated X and Y coordinates of the public point. While this normally ensures the generation of shared secret key, forward secrecy is also provided by making this process ephemeral, new parameters being generated for each request. Non repudiation is assured by providing a digital signature of the Base64 representation, signed with the device’s private key. The useful information is then formatted as a JSON object and sent to the attestation server. On receiving the payload, the server will attempt to retrieve the certificate of the other party by using the IP of the request. If no such certificate is present, the attestation process will halt, sending HTTP status code 400 Bad Request in response. Otherwise, the public Diffie Hellman parameters and the signature will be decoded from Base64. Using the public key from the certificate stored in the previous attestation step, the signature is verified. Since the data exchange was performed over an unsecured transport protocol, assuring the integrity of the data is of utmost importance. If the signature doesn’t verify, it means that the payload has been tampered with and the attestation process will stop, returning the same HTTP 400 Bad Request code as before. If the signature is valid, the server generates its own set of Diffie Hellman parameters, packages the public point using the same format as the node, concatenated value of X and Y encoded using Base64, and signs the representation. Along with the aforementioned components, a 16 bytes random sequence is generated in order to ensure that the same session key is generated by the both parties. Since the server already has all the ingredients needed to establish the secret key, it will be generated at this step and saved in secure storage. The response is then sent to the IoT node in the form of a JSON object.

The third and last step of the attestation process is represented by the */clientFinish* HTTP POST endpoint. Before issuing the request, the node decodes all the parameters from the */keyExchange* from Base64 and verifies the signature of received data. If the signatures doesn’t verify, an error message is logged and the node restarted. Otherwise, it instantiates an elliptic curve point based on the server X and Y points and uses it along its own Diffie Hellman parameters to generate the shared secret. Besides generating a shared key and attesting the origin of the node, this process also allows the IoT node to present its capabilities to the attestation server, along with several identifying information. These capabilities should be tamper resistant. Several solutions were candidates, such as using a salted message digest to ensure data integrity, since otherwise if no salt was used an attacker could just recompute the hash of the desired value, digitally signing the capabilities, or using an encryption algorithm. Even if in the case of encryption, the data would be irrecoverable when tampered with, confidentiality will be ensured while still a mean to determine any tampering attempt. The device identifier consists of the MAC address of the IoT node’s WiFi card, an uniquely identifying property of the node since this is burnt into the chip at manufacture time and doesn’t allow permanent change, along with the list of capabilities formatted in an IPSO Smart Object friendly way. As such, the capability is identified by an object ID, which uniquely identifies a singular measurement value, e.g. temperature, and a list of resources presented by the object. The resources are identified by an ID, and represent a certain piece of information the object can provide, e.g. maximum temperature, minimum temperature, current value. This identifier will then be appended to the test bytes sent by the server and encrypted in AES/CBC mode using the newly generated shared key, setting a randomly generated 16 bytes sequence as initialization vector. Since the initialization vector is not secret, nor the resulting ciphertext, these are concatenated and encoded in Base64 to be sent in the request body. On receiving the request, the server decodes the payload from Base64 to a byte array representation, which is then split into IV and ciphertext arrays. Based on the IP of the request, the previously generated secret key is retrieved from secure storage, removing it in the process. If no such key exists, the attestation process is marked as failed and HTTP status code 400 will be returned. Otherwise, the ciphertext is decrypted and the first 16 bytes of it are checked against the previously sent test bytes sequence. If the bytes don’t match, the process is ended as failed and HTTP status code 400 will be returned. In an attempt to save computational effort, the generated secret key is then used by the node in order to establish MQTT connection in TLS-PSK mode. As such, the attestation server also handles the insertion and removal of PSK keys in the broker configuration file. The MQTT broker expects the file that stores the pre-shared keys to be formatted as *hint:key*, where key is the Base64 representation of the secret key. On each new modifying operation on the secure storage that handles PSK keys in the attestion server, the whole content of the file is overwritten by the keys saved in the server using the previously specified format. In order for the changes to take effect, a Java ProcessBuilder had to be used which calls a shell script on the host machine. As such, a limitation can be observed, the tight coupling of the attestation server with the MQTT broker.

Diagram, schematic

Description automatically generated

Figure 3‑5. Last step of the attestation process

Besides restarting the broker, the server also sends the device identifier to the OLTP microservice in order to have the node information persisted. The request is made via HTTPS which offers transport layer security thanks to TLS, and also authenticated using JSON Web Tokens.

The authentication and authorization of users is delegated to Auth0, the latter issuing and verifying the tokens. In order to obtain an authorization code, an HTTPS POST request is sent to the issuer URL which in turn verifies the client’s data and returns a Bearer Token. This token must be bundled with each request that requires authentication, in the Authorization header.

In order to save computational effort, the session key is persisted after a successful attestation process alongside the timestamp it was generated and the digital signature of aforementioned properties concatenated. Forward secrecy is achieved by expiring the key every 24 hours, undergoing the attestation process again after this period in order to generate a new key. This ensures that a compromised key can not be used to decrypt past ciphertext.

On the same machine that the attestation server is hosted resides the MQTT Broker, in the form of Eclipse Mosquitto. The broker was setup to allow incoming connections over TLS, be it either with pre-shared keys on port 8883 or with certificates on port 8884. Two listeners were used instead of one in order to provide more flexibility, the certificates endpoint being easier to approach with applications running on more conventional computers with x86\_64 or aarch64 architecture since those have more processing power and leverage the already existing Public Key Infrastructure, while the IoT nodes use the pre-shared keys listener since the key is generated during the attestation process. The broker will forward all published messages to the corresponding subscribers, while also allowing persistence of last message for each topic with the purpose of distributing to newly subscribed applications. The delivery guarantee is affected by the Quality of Service flag, ranging from 0 to 2; 0 is the *At most once delivery* mode, where no response is sent by the receiver and no retry is performed by the sender, hence no guarantee is offerted. 1 is the *At least once delivery* mode, where the packet is acknowledged by the sender with a *PUBACK* packet. Mode 2 offers the highest guarantee, *Exactly once delivery*, for use when neither loss nor duplication of messages are acceptable.

While the broker comes pre-configured with sensible default settings, a custom configuration was created and placed inside the */etc/mosquito/conf.d* directory. This directory is specified as the include directory in the global Mosquitto settings.

Text

Description automatically generatedText

Description automatically generated Figure 3‑6. Global Mosquitto Settings Figure 3‑7. Custom Mosquitto Settings

Besides the aforementioned options, some other settings are mandatory depending on the security scheme used. For PSK secured listener, a *psk\_file* must be specified which stores the pre-shared keys in the *hint:key* format, where the key is the Base64 representation of it the PSK. Since the key is the result of the attestation process, the classic username and password combo for authentication can be skipped by setting the *allow\_anonymous* option to *true*.

For the listener secured by using the Public Key infrastructure, the certificate of the CA must be specified, along with the server key pair. The presence of certificates at connection time can be enforced by setting the *require\_certificate* option to *true*, while also using the subject of the certificate with *use\_identity\_as\_username* to *true*. To ease development, the certificates were self-generated instead of using a renown Certification Authority. This practically created my own Public Key Infrastructure, being able to sign an unlimited number of certificates. For all the certificates, OpenSSL was used to create the private keys, certificate signing requests and the certificates.

First of all, the CA key-pair had to be generated. Since this is the root CA, it is self signed. After this step, the server key-pair can be generated, making sure to specify in the Subject Alternative Name X509 v3 Field the IP address of the broker it is supposed to be installed on. Such a field can be populated using OpenSSL after creating the certificate signing request by specifying the *-extfile* option:



Having generated these certificates, the server part of the setup is done; also, each client that needs MQTT client connection is provisioned with its own key-pair signed by the certification authority.

Besides the security options, the *pid\_file* option is specified in order to allow the attestation server to restart the broker. This option writes at broker startup the process ID of Mosquitto. The restart is not done directly, but by using the aforementioned ProcessBuilder that calls the *restart.sh* shell script. This scripts reads the content of the PID file, kills the process using *SIGKILL* command and starts a new instance of the broker.

Graphical user interface, text

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Figure 3‑8. Restart shell script

As it can be seen in the restart shell script, the broker can be started by using *mosquito -v -c <config\_file>*, where *v* stands for verbose and *c* points to the configuration file used, or by using *systemctl* if using a Debian based distro.

Text

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Figure 3‑8. Starting the broker using systemctl

a

# **CONCLUSION**

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