

An Open Source Framework for Building a Smart Home

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1 Introduction

The advent of the Internet of Things (IoT) has revolutionized the way we interact with our environment. The IoT is the concept that everyday devices can be turned into "smart" devices, by connecting them to the internet. Devices that were constrained on interaction, be it for practical or aesthetic reasons, can now communicate with not only humans, but also devices surrounding them. Instead of giving devices displays, they can instead communicate through the web, possibly enhancing their utility and making them cheaper to produce. The idea of the IoT emerged in the early 90s from Mark Weiser [17] and has since paved the way for devices integrated into our everyday lives, in so-called "Smart Homes".

Enabled by the IoT, Smart Homes are internet connected homes, that allow the user to interact with them in unconventional ways. A lightbulb that is turned on with the users phone instead of a switch, a stereo system that plays music with the press of a button on the users phone. While both these technologies might even seem common place in 2024, they are both directly enabled by IoT and are relatively recent inventions, enabled by the proliferation of wireless technology. While smart home technology may seem mundane at this point, a major issue in the space is the lack of open source standards and frameworks, that not only allow the user to build and connect their own IoT devices to a smart home network, but also provide a server for the devices to connect to and a frontend that allows the user to control the device. This thesis argues that the development of an open-source IoT framework can address these issues.

This bachelor thesis aims to delve into the creation of an Open Source IoT system, including a library/framework for the creation of IoT devices, the server for these devices to connect and communicate with, and a web based frontend to control these devices from. It will contain an explanation of various design decisions made throughout this process, excerpts and explanations of code from the open source library and test results of the final product. It will also include the code for an example device created to interface with this system, using the device creation framework. These contributions to the IoT world will make it easier for anyone with a rudimentary knowledge of programming to create their own internet connected "smart" devices and perhaps provide a pathway for someone interested in building their own smart home to follow.

1.1 Aims & Objectives

When researching available smart home technology, one major gap I came across was the availability of open source software. While options exist for someone interested in connecting their proprietary device to an open source platform, for example a project called "Home Assistant" there was no solution for anyone looking to build their own device and then connect it to an open source hub. In fulfilling this goal, to build an open source platform for both devices and the hub they will connect to, there are multiple objectives that will need to be met along the way:

1. Create a framework to aid developers in building smart home devices.
2. Build a Server with an API (Application Programming Interface) for the smart home devices to communicate with. This will act as a hub and will control clients connected to it.
 - a) This API should be well documented, so a user can interact with the hub, without using the Library.
3. Create a frontend, which will be populated with devices currently connected to the smart home. It will also be used to control clients connected to the server.
 - a) The API provided by the server for this frontend should also be easy to use, so the user can create their own frontend environment.
4. The code of all of the above should be hosted in a public repository, with instructions for how to build and use every component of the system.
 - a) An appropriate license should also be selected for this repository, so the code within it can be copied or modified by third parties.
 - b) This repository should provide important links and provide information on the inner workings of the system, to support interested parties.

1.2 Project Overview

1. **Literature Review:** This section will provide an overview of works related to Smart Home and IoT technology. It will also include sections about API design.
2. **Design:** Here the overall design of the system will be detailed, including project architecture, technology choice and the theoretical security systems that will be implemented.
3. **Implementation:** The implementation section will provide a lower level explanation of code snippets and how the actual system was implemented. It also discusses how the library can be used and the final design of the frontend that was implemented.
4. **Testing & Evaluation:** This section will the methodology and results of different tests carried out on the system, including performance and usability testing.
5. **Discussion & Conclusion:** This final section will provide a discussion of the results of this project and some final statements.

2 Literature Review

This section will provide an in-depth analysis of different concepts mentioned in the literature related to building an IoT-System, specifically a Smart Home. This includes different IoT architectures, important factors that make a successful IoT system and different types of API designs.

2.1 IoT System Architectures

Kamienski et al. describe a simple three layer architecture of an IoT system in [14]. Within this architecture, the top layer is the "Input System", from which any data that will influence the decisions of the IoT system will come from. Included in this are sensors, but also user facing interfaces. The second layer, known as the "Process System", is where any algorithms are run and system behavioral decisions are made. The goal of this layer is to gain an "improved understanding of the system where the data comes from" [14]. The bottom layer is the "Output System", which are where decisions made by the Process System will be enacted. This is often represented as the devices connected to the IoT system.

This three layer architecture is expanded upon by Bansal and Kumar within [5], where three more architectures are described which expand upon the ideas within the three layer architecture. They are however more specialized than the three layer architecture. The first of these is a "Middleware Based" architecture, which can take many forms, but is usually combined with another type of architecture, with a middleware layer. The different types are described in detail by Zhang et al. in [21]. The second is known as a "Fog Based" architecture, where certain tasks, usually those with less processing requirements, are calculated on device to reduce latency. More computationally expensive tasks are however calculated on a server in the cloud [18].

The most relevant architecture to this report is known as a "Service Based" architecture (SBA). The SBA is defined around the concept of the Service Oriented Architectural (SOA) style [12] of software design. SOA is defined by the Open Group Foundation as an "architectural style that supports service-orientation", where a service is a "logical representation of a repeatable business activity that has a specified outcome" [3]. Each service is a "black box" any device interacting with it. Other devices use interfaces and API endpoints to make requests to the service and receive a result. A SOA is composed of many different services. In SBA, services are used to offer device functionality using interfaces, often using web based concepts such as SOAP or REST APIs [8]. This allows devices with different capabilities and purposes to interact with the same system, allowing for an IoT system that is more flexible.

The SBA architecture was chosen as the most appropriate for this project. Due to the server having to serve a variety of functions, such as serving both the frontend and the devices, while potentially also needing to connect to a database, separating these into services seems like a good idea, with each device only accessing the services it requires.

2.2 The Smart Home System

Sethi and Sarangi [18] define six components that need to be present within a social IoT setting. A social IoT system is defined as a IoT system where devices form relationships with other devices. While our smart home system will not be a social IoT system, some of these concepts are still of interest. These are:

1. ID: the device within the system needs to have a way of identifying it.
2. Meta-data: the device should have information regarding its form and purpose
3. Security Controls: the system should have some way of distinguishing between different users. It should also be able to distinguish what types of devices it can connect to or can connect to it.
4. Service Discovery: each device should be able to discover other devices connected to the system and what services they offer.

There are some specific constraints specific to Smart Homes. Reliability is a key concern, due to the lack of a trained professional being available to fix any issues that arise. This is contrast to more industrial IoT settings, where there might be someone to fix any issues that arise. Another concern is the security and privacy of the system. Due to smart homes inherently having access to sensitive data (due to their position in someone's home), one must ensure that the system is both ethically sound and secure. The issue of security is further discussed in Subsection 3.3.

2.3 APIs and Web Interfaces

The book "Designing Web APIs" makes an important distinction about APIs that can often be forgotten by developers. "Although APIs are designed to work with other programs, they're mostly intended to be understood and used by humans writing those other programs" [13]. Due to this reality, one must remember to design APIs appropriately. To help the API designer in doing that, there are multiple pre-defined architectural standards that they can use.

2.3.1 Request Response

"Request Response" APIs (RRA) expose their interface through a web server, to which clients can make requests. A client will request data and will receive a response from the server. Common formats for requests and responses include JavaScript Object Notation (JSON) and Extensible Markup Language (XML). [13].

One popular type of RRA is known as Representational State Transfer (REST). Two important properties of REST is that it is used in Client-Server scenarios and that every request is stateless [10]. This means that every API request from the client to the server, must contain all information required to complete that request, without the server storing any of that information. Instead, all state is stored on the client. While this constraint might seem strange, it makes any API implementing REST easily scalable, and potentially easier/faster to build. The downside being inherently increased network traffic, with less control application behavior. [10].

Another popular implementation of a RRA is known as the Remote Procedure Call Architecture (RPC). The key difference between RPC and REST is that RPC is about

making an action on the server. In REST the client supplies the server with the information required to take an action, whereas using RPC the client tells the server what action to take. RPC APIs can usually express more nuance in their requests and are generally stateful. While RPC usually uses JSON or XML for requests and responses, there are multiple implementations, such as Google's gRPC and Apache Thrift, which do not. These are usually serialized and therefore consume less network traffic than non-serialized formats such as the aforementioned JSON [13].

2.3.2 Event Driven

Event driven APIs go in a different direction than RRAs. Instead of the client continuously requesting information from the server, the client registers with the Server once, then whenever there is an update the server sends the client a message notifying it of an update. This completely resolves the need for polling, the client continuously requesting updates from the server, which is often present in RAA API designs [13].

Web sockets are a type of Event Driven API that utilize a bidirectional TCP connection between server and client. Unlike the previously mentioned API styles, a connection on a web socket stays active until closed [4]. Due to the bidirectional TCP connections both client and server can send one another packets, even at the same time [13]. This is in contrast to REST and RPC protocols, where only the client can contact the server. This comes at the downside of scalability, as a server must maintain a connection with every device that is connected with the server. Additionally, there are also issues when a client is on an unstable connection, as web sockets expect a client to stay connected, with the client having to reinitiate the connection if it is dropped [13].

The final type of API that deserves a short mention is the Web Hook. Web hooks work in an unconventional manner, where the initiator of an exchange gives a URL to their own API endpoint. This URL is then used by the receiver. Whenever a new event for the initiator occurs, the receiver will send information about the event to the URL [13]. While at face value this may seem like an obvious solution in an IOT based environment, where devices are often waiting for an event from the central server, it makes less sense when one realizes that every device connected to this webhook will need to host some sort of HTTP server, to receive the API requests. This makes it unsuitable, especially in environments where IOT devices are low powered, embedded systems devices. Web hooks are often used in server to server communication, as in such a scenario they are trivial to set up (as servers will most likely already be setup to receive API requests) [13].

2.3.3 My Choice

For the purposes of this project two options seemed most appropriate, web sockets and RPC. Web sockets would be useful, as the server could send frontend requests directly to connected devices, instead of waiting for polling. However, I decided to go with RPC, as Web sockets would require an open TCP connection to every connected device, which would require significant resources from both the server and devices. It would also limit the amount of devices able to connect to the server. RPC provides an easy programming interface to work with and is very performant (further discussed in subsection 3.1.

3 Design

This chapter will describe a variety of design decisions made throughout the process of this project. It aims to give a higher level overview of how systems work, in comparison to the implementation chapter of this report. It will detail different technology used throughout project and the reasons behind these choices and also give a higher-level, more mathematical view of the security measures implemented. Finally, it will show preliminary designs of the web-frontend.

3.1 Technology Choices

This section will discuss choices that have been made throughout the project regarding technology used and justifications for their usage.

3.1.1 Rust

There were a few requirements when choosing an appropriate programming language for this project:

1. Performance: Optimization is crucial for IoT devices due to their limited processing power. Server performance can be scaled more easily, however is still an important consideration.
2. Stability: The language should encourage memory-safe and error-handled code, as IoT devices and their servers need to run for long periods without crashes and memory leaks.
3. Security: The language should promote secure coding practices. A blog-post by the "Microsoft Security Response Centre" states that 70% of all vulnerabilities assigned a CVE (Common Vulnerabilities and Exposures) each year are due to memory corruption errors [20].
4. Ease of Use and Comfort: A user-friendly language can speed up development and design iteration, possibly improving the final product, but familiarity with a language can compensate for this.

The language that was chosen for this project was Rust. While C/C++'s performance rivals and often surpasses Rust, the difference is often quite marginal [16], due to all three being compiled to machine code. What makes Rust different, is its headline feature, known as the "borrow checker". It can ensure that at compile-time, the code is memory safe. Due to the code being guaranteed memory safe at compile time, outside explicitly marked unsafe blocks, Rust code is known for its ability to run long-term without running into crashes. Additionally, Rust code is a popular choice for embedded devices, due to being able to compile without a standard library, giving it flexibility in a project such as this. Finally, even though it is known as a difficult language to learn and master, personal familiarity with Rust makes it an obvious choice for this project.

Note: throughout this report some Rust terms, such as library and crate, will be used interchangeably. They are however different in certain ways. For a full explanation of some of these terms view appendix section C.1.

3.1.2 gRPC

gRPC is an RPC implementation released by Google in 2015. It uses Protocol Buffers (protobufs) as an interface definition language (IDL), to define services on servers, that clients can then call. The server runs a gRPC server and the client runs the gRPC client [11]. Protobufs can be compiled to many different languages, including Rust and Typescript. In a performance comparison between REST, gRPC, websockets and GraphQL, gRPC came out ahead in many different metrics [15] in both native and containerized tests. In fact, gRPC was the most performant internet communication protocol in all metrics apart from memory usage.

Due to its performance and cross-language support I have chosen gRPC as the internet communication protocol for this project. The specific library used for this project is known as "Tonic". Tonic is a Rust gRPC crate that includes both a gRPC server and client. It also utilizes an additional Rust library named "prost", to compile protobuf files into Rust code, without having to interface the protobuf compiler itself.

3.1.3 Typescript & VueJS

While a Command Line Interface (CLI) frontend, written in Rust, will be made available, the main focus will be on the Graphical User Interface (GUI). To ensure that it can run on a variety of systems and is relatively easy to create, it will be web based, using Javascript at runtime. However, it will be written in Typescript. Typescript is a superset of Javascript, that compiles to Javascript and leaves no trace of types behind. Typescript provides a robust type-system, including, but not limited to [6]:

- Structural type equivalence, instead of Javascript's by-name type equivalence
- Types and concepts for object-based programming
- Type operators

All of these, while not guaranteeing that the program will be type-safe at runtime, help a developer design more robust and long term solutions generally associated with statically typed languages.

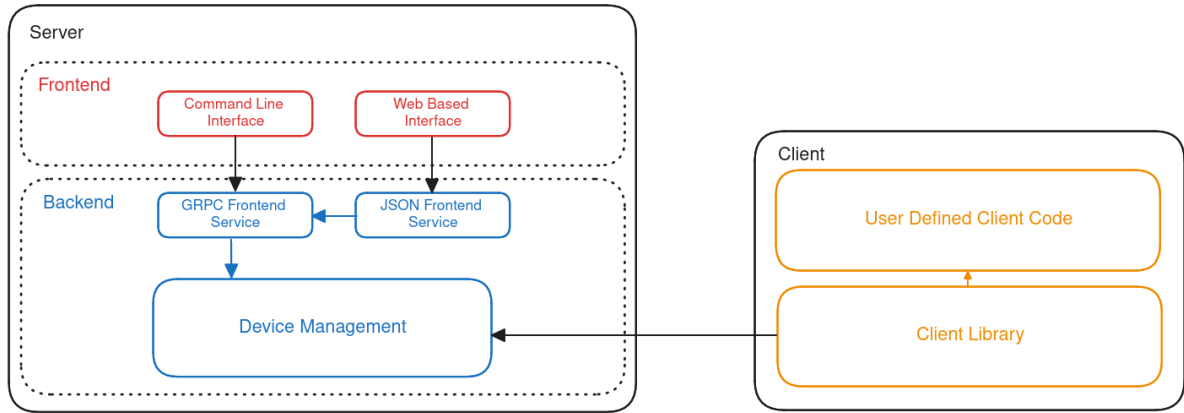
In conjunction with Typescript a web-development framework will be used. Web frameworks are libraries for Javascript that allow easier development of websites and web apps, often incorporating HTML (HyperText Markup Language) and CSS (Cascading Style Sheets) code into Javascript code. They also provide reactivity, meaning that if a variable changes in the code, that change can easily be reflected on the site. This can be done in most frameworks by simply using the variable in the HTML code, something that standard HTML does not support (methods of doing this differs between frameworks).

Web-framework choice often hinges on personal preference and familiarity. Performance differences exist between frameworks, but they're usually negligible and shouldn't dictate choice. While there is a lack of formal experiments on framework performance, an informal experiment [7] shows performance differences between most major frameworks being negligible. Due to this and personal familiarity with the framework, VueJS was chosen for this project's frontend.

3.2 System Architecture

The overall system architecture can be seen in figure 3.1. This system architecture consists

Figure 3.1: System Architecture



of two main components, the server and the client. Here the server represents the main controller of the system. The client is any device connected to the system (there most likely will be multiple). One peculiarity, is the fact that the frontend is contained by the server part of the system. This is because, in the current design, by default the frontend will be run on the same machine as the backend, with frontend API endpoints (located in the frontend services) being open on the localhost loop back address. This can however be easily changed by a user, by simply changing the address the frontend API endpoints are hosted on.

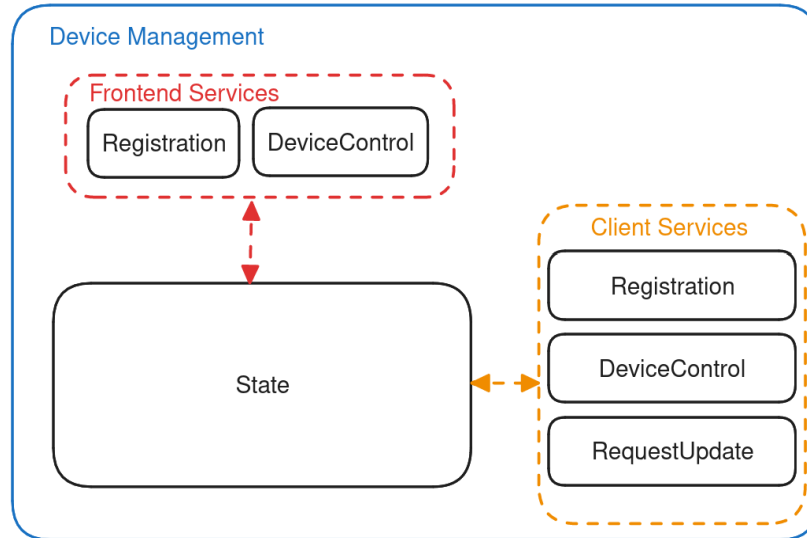
The arrows in the architectural diagram represent the direction of contact. For example, a client can contact the backend and the backend may respond, however the backend cannot contact a device, it can only reply to a request. The only deviation from this rule is within the client. At startup, the user will supply the client library with callback functions, which the library can call. This means that the user defined code must be able to contact the client library during setup. However, once the client library has finished setup and has created contact with the backend, the user defined code can no longer interact directly with the client library. The library will then simply call any code supplied to it during setup, without having any direct contact with user defined code.

Figure 3.2 shows the architecture of the "Device Management" part of the backend of the system architecture. Device Management is comprised of several services, being based on the SBA architecture discussed in section 2.1. Each service has its own function and is independent. However, they all access the same state and are all defined in protobuf files and can therefore all having functions that can be called using gRPC.

3.3 Security

As previously discussed, security is an important concern within a smart-home environment. The user of the system is putting trust into the system to behave as it is meant to, while keeping their personal data safe from outside intruders. That is why special

Figure 3.2: Device Management Architecture



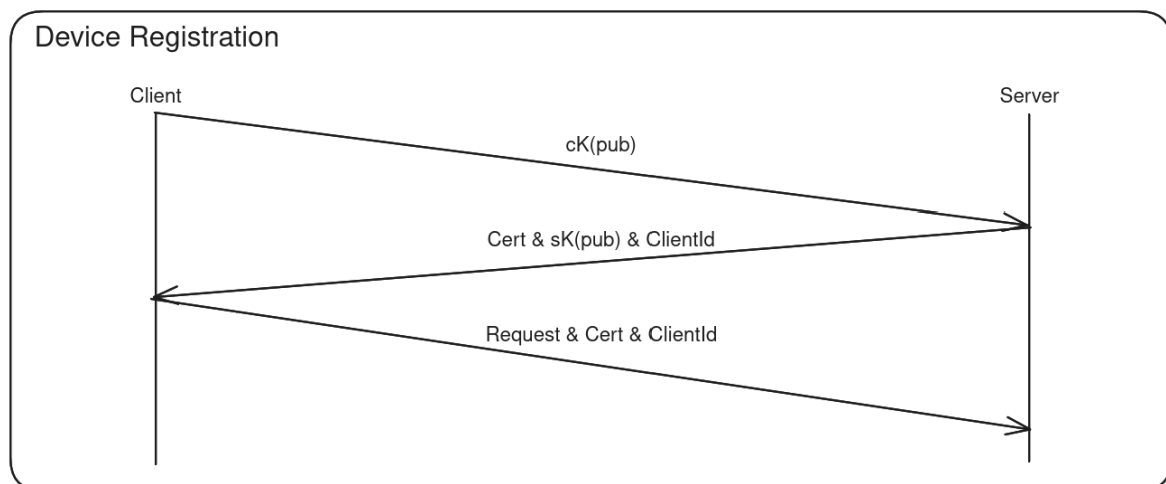
care will be put into the security aspects of the system. This will come in a two pronged approach using certificates and signatures.

3.3.1 Certificates

A certificate is a tool for verifying that a client is who they say they are. It is generated by the server and can be verified by the server. This is useful, for example, if the client goes offline and at a later time wants to re-authenticate with the server. They can send the certificate provided to them earlier and the server can verify it. The certificate scheme that will be implemented is based on [9].

Figure 3.3 shows the certificate exchange protocol that will be used, where cK is the client key pair and sK is the server key pair. $K(pub)$ represents the public key part of the key pair.

Figure 3.3: Certificate Exchange



At startup the server and client will both generate an asymmetric key pair using the Rivest, Shamir, Adleman (RSA) public key system. Then, during registration, the client will send the server their public key. The server then creates $csr = cK(pub) + ClientId$. Csr is then hashed using SHA256 hashing to create the certificate: $certificate = H_x(csr)$. This certificate is then sent back to the client, along with the server public key and their client identifier (which is a UUID randomly generated by the server). Now, if the client goes offline and wants to re-register, instead of having to repeat the registration process again, they can simply include their certificate instead and be verified by the server. Verification is quite simple. The client simply re-generates csr using the client's public key and client-id, then re-hashes them. If the new hash is the same as the certificate, then the client is verified.

3.3.2 Signatures

Signatures allow both the server and client to verify that the messages they are receiving are not forged and sent by a third party. The signatures will use the key-pairs generated and exchanged during registration (view certificate exchange), to sign every message with a hash, that can be independently verified by the other party. The message sender will use their private key to sign their message and the receiver will use the public key send during registration to verify the message. This signature scheme is based on concepts described within [9] and [19].

Every signature will consist of three important parts:

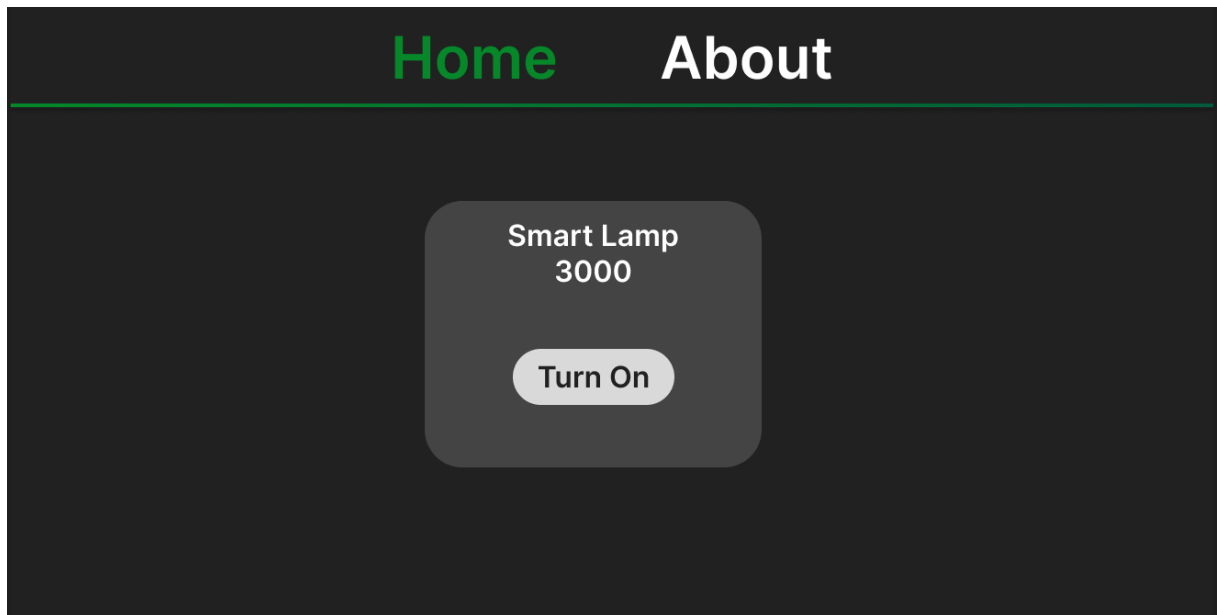
1. Unix Timestamp - This will be used to prevent replay attacks. Every message will include the Unix timestamp of when it was sent and this information will be included in the signature. The receiver can then check the age of the message and discard it if it is beyond a certain threshold.
2. Message Contents - This is used to ensure that the contents of the message stay the same between sender and receiver. Because hashing the entire contents of a message might be costly, some subset of the contents must be chosen. This will depend on the message type.
3. Certificate - The certificate is included in the hash, however not in the message. This is an extra layer of security, as both server and client have an independent version of the certificate, meaning that an attacker would also need to obtain this certificate somehow, along with the private key of the sender.

Every message will include a signature, which must first be verified by the receiver before the information within the message is processed. This is help ensure that data can not be tampered with between sender and receiver.

3.4 Web Frontend

Figure 3.4 shows a mockup what the home-screen of the web frontend should look like. The main focus should be on the devices, which will be represented by boxes on the home screen. The device's available capabilities will be shown as buttons or sliders, configurable from the device itself. As the focus of this project is mainly on the system and the API of the device server will be available, custom web frontends should be easy to make, for a more customizable experience. Due to the whole project being open-source, this frontend can be built upon by other users, or companies, interested in customizing it.

Figure 3.4: Home Screen Mockup



4 Implementation

This chapter aims to provide a low-level, in-depth explanation of how a variety of systems work throughout the project's codebase. It provides code samples, with explanations of what that code is doing, to give insight into how this project was built. It does this through describing all aspects of the Registration Service. Throughout, how devices connect using the Registration Service, how these devices are registered in the server and how this information is reflected on the frontend are described in detail. This information can then be extrapolated to the other services present within the overall system.

4.1 Backend Server & Device Management

Due to the server being the largest part of this project, and practically being a requirement for testing the client and frontend functionality, this will be focused on first. This section will describe defining and compiling protobuf files for API endpoints, server startup, how IOT devices are registered, security mechanisms and how concurrency was handled within the server.

4.1.1 Protocol Buffers

Remote functions accessible through gRPC are defined in ".proto" files. They use a fairly basic syntax, where the user can define a service using the "service" keyword. A service can contain many functions which a client can call, these are defined using the "rpc" keyword. Structs are defined using the "message" keyword, where each field is separated by a semicolon. These structs will then be compiled to their corresponding datatype in whatever language you are using. For example, they are compiled to classes in Typescript or structs in Rust. This makes them useful if a datatype is shared between languages, they can be defined in one protobuf file and used across languages. Protobuf structs contain fields, which can have multiple modifiers, including optional and repeated. Repeated marks a field as possibly being a list, or array structure, optional marks a field as optional (represented differently between languages). Finally, messages from other files can be imported. Below is the service definition for the RegistrationService, found in *protos/iot/registrationService.proto*:

```
1 syntax = "proto3";
2 package iot.registration;
3 import "types.proto";
4
5 service RegistrationService {
6     rpc Register(
7         RegistrationRequest
8     ) returns (RegistrationResponse);
9 };
```

```

10
11 message RegistrationRequest {
12     string public_key = 1;
13     string name = 2;
14     repeated iot.types.DeviceCapabilityStatus
15         capabilities = 3;
16 }
17
18 message RegistrationResponse {
19     string public_key = 1;
20     string client_id = 2;
21     string certificate = 3;
22 }

```

Here we define a service called "RegistrationService", with a function called Register. This function is called by IOT clients when they first attempt to connect to the server which takes a RegistrationRequest as a parameter and returns a RegistrationResponse. The file also defines two "messages". The capabilities field is repeated, meaning it is an array data structure. This array contains the type DeviceCapabilityStatus, which is defined in iot.types. We can see this type is imported at the top of the file, from "types.proto". This is the definition of DeviceCapabilityStatus:

```

1 message DeviceCapabilityStatus {
2     bool available = 1;
3     string capability = 2;
4     DeviceCapabilityType type = 3;
5     optional float value = 4;
6 }
7
8 enum DeviceCapabilityType {
9     BUTTON = 0;
10    SLIDER = 1;
11 }

```

In summary, if an IOT device wants to register with this server, they will need to call the Register server stub. The server stub takes one parameter, the RegistrationRequest message. This message requires the client to give it's public key, it's display name and an array of "DeviceCapabilityStatus". The Register function then returns a RegistrationResponse. To see how this service is implemented on the server, view subsection 4.1.3.

4.1.2 Server Start Up

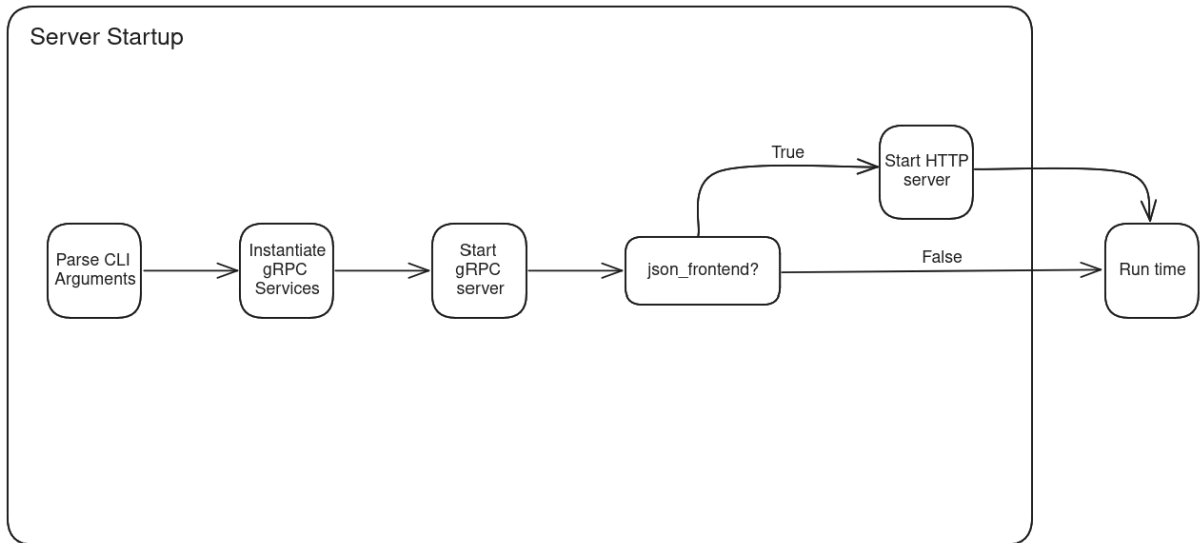
This section will describe what is done when the server first starts. It will give a general overview of startup and the details of starting a gRPC and HTTP server in Rust. For more details, view the main function within */backend/src/server/server.rs*.

Startup of the server is currently quite simple:

Command Line Arguments

Command line (CLI) arguments are parsed using a Rust library called "Clap". Currently the only commandline argument that can be passed is running the optional HTTP server,

Figure 4.1: Simplified Diagram of Server Startup



which enables using JSON for the frontend (view subsection 4.3.3), however there are plans to include other arguments, such as giving an IP address or Port for the gRPC server to run on as an argument. Currently, the computer's IP address is discovered automatically using a crate called "local-ip-address".

Creating gRPC Services

Next gRPC services are instantiated. GRPC services in Rust take the form of structs that implement the trait (interface) defined as a service within a protobuf file. Take for example, the "RegistrationService" from *protos/iot/registrationService.proto*, defined in subsection 4.1.1:

```

1 service RegistrationService {
2     rpc Register(
3         RegistrationRequest
4     ) returns (RegistrationResponse);
5 };
  
```

This is implemented on a struct in Rust like this (code snippet from *backend/src/server/registration.rs*):

```

1 use self::registration_service
2     ::registration_service_server::RegistrationService;
3
4 #[async_trait]
5 impl RegistrationService for ClientRegistrationHandler {
6     async fn register(
7         &self,
8         request: tonic::Request<
9             self::registration_service::RegistrationRequest
10        >,
11     ) -> RPCFunctionResult<
12         self::registration_service::RegistrationResponse
  
```

```

13     > {
14         //code goes here
15     }
16 }

```

Where "RegistrationService" is an interface, defined in a protobuf file (view subsection 4.1.1). "ClientRegistrationHandler" is the name of the struct this interface is being implemented on. If the interface is implemented correctly, this struct is now a service and, after being handed to the gRPC server struct, this function can then be called using a RPC through gRPC. In other words, any gRPC client that is connected to this gRPC server can now call this function, as long as their programming language supports it.

Starting the gRPC Server

After implementing all services defined in the protobuf files on appropriate structs, the gRPC server can now be started. This is done in the following code snippet from */backend/src/server/server.rs*:

```

1 use registration_service_server::RegistrationServiceServer;
2
3 let registration_service =
4     registration::ClientRegistrationHandler::new();
5 let grpc_server = tonic::transport::Server::builder()
6     .add_service(
7         RegistrationServiceServer::new(
8             registration_service,
9         )
10    )
11    .serve_with_shutdown(
12        grpc_address,
13        tokio::signal::ctrl_c().map(drop)
14    )
15    .await;
16
17 println!("Started GRPC Server on {}", grpc_address);

```

Note that the above code snippet is abbreviated for readability, it is however still valid Rust code and gives a good representation of what is done in server.rs.

The Server struct we are instantiating on line 1 comes from the transport module within the tonic crate. We invoke the builder method on the Server struct, a very common pattern within the Rust ecosystem. In fact, the same pattern is used to instantiate a new IoT device in the client library for this project (view section 4.2). After invoking the builder method, which returns a new Server struct, we add structs that implement the aforementioned services to it, using the "add_service" method. In our case, we want to hand it a "RegistrationServiceServer" struct, provided by the protobuf file. The "new" method on the "RegistrationServiceServer" takes one argument, which is a struct that implements the "RegistrationService" trait, which is the trait we implemented on our ClientRegistrationHandler earlier. We therefore hand it the variable "registration_service" which is of the type "ClientRegistrationHandler".

The "server_with_shutdown" method consumes the Server struct and runs the server, on the address handed to it in the parameter. In this case it is the variable "grpc_address",

which is a string which contains the device's IP address and a port. The second parameter simply tells Rust to drop the gRPC server (shutdown and gracefully free the memory associated with it) when the key combination ctrl-c is pressed. This is an easy way to implement this behavior in Rust when working with multiple threads (view subsection 4.1.5).

Once we have added all services to the Server struct, it must be awaited using the "await" keyword. For more information on how this works view subsection 4.1.5.

Starting the HTTP Server

Starting the HTTP server works almost the same as the gRPC server, using the same builder pattern. However, this time instead of using the Tonic crate, we are using a crate named "Actix", a self-described "powerful, pragmatic, and extremely fast web framework for Rust" [1]. View part of the "run_json_frontend" function, found in the file *backend/src/server/server.rs* below:

```
1 const JSON_ADDRESS: &str = "localhost:50052";
2
3 let result = actix_web::HttpServer::new(move || {
4     actix_web::app::App::new()
5         .app_data(web::Data::new(json_state.clone()))
6         .service(json_registration::json_registration)
7 })
8 .bind(JSON_ADDRESS)?
9 .run()
10 .await;
```

Note that the above code snippet is abbreviated for readability, it is however still valid Rust code and gives a good representation of what is done in server.rs.

Due to this builder function requiring more Rust specific knowledge to understand, it will be simplified here. It is functionally the same as the one seen from Tonic. First we create a new HTTPServer struct from the actix_web module. We then hand it our services using the "service" method. What is different here, is that we are actually handing it callback functions, instead of structs with traits implemented. To view an example of these services, view subsection 4.1.3. From there we bind this server to the constant string JSON_ADDRESS. This is an IP Address defined at compile time, the definition however is found above the web server. The server is running on localhost, as it is meant for communication with the web frontend. We then call the run method and await the result. In reality the server is being awaited on a different thread than the gRPC server, so the two can run concurrently. This is not shown in the above code snippet.

For code beyond the above provided abbreviated snippets view the file *backend/src/server/server.rs*, which contains the main function for the server.

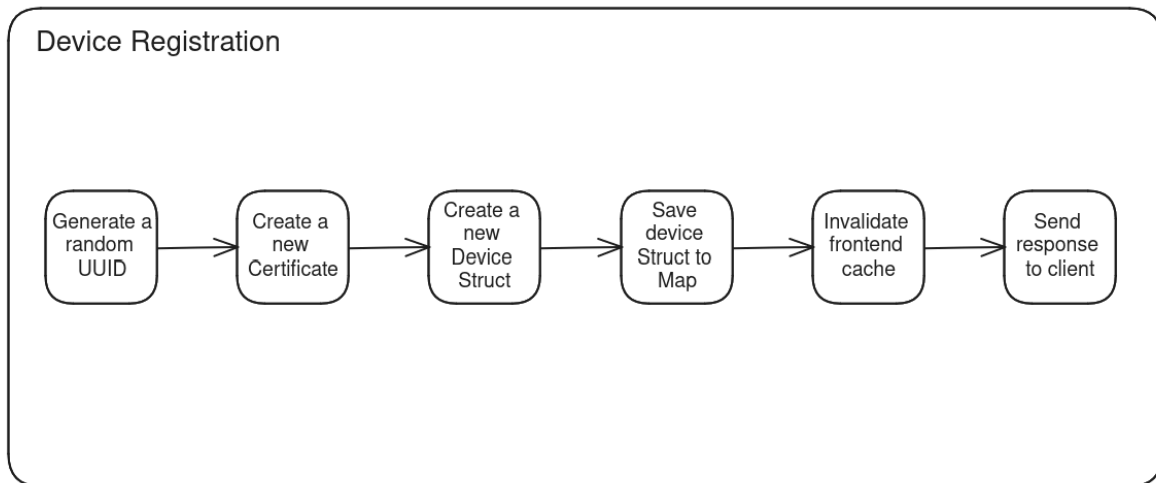
4.1.3 Device Registration

This section will give an overview of the server's response to a device registration attempt. For information about how registration is performed on a device, view subsection 4.2.2

Figure 4.2 shows the process of the server receiving a registration request from a client:

When a device wants to connect to the server, it uses the "Register" function from the "RegistrationService" through gRPC. To do so, it must first create a "RegistrationRe-

Figure 4.2: Simplified Diagram of Device Registration



quest", the contents of which are detailed within the *proto/iot/registration.proto* protobuf file:

```
1 message RegistrationRequest {
2     string public_key = 1;
3     string name = 2;
4     repeated iot.types.DeviceCapabilityStatus
5         capabilities = 3;
6 }
```

This is the same protobuf code as in subsection 4.1.1. The "RegistrationRequest" contains the device's public key and its display name. The public key will be used for encryption and signing, the name is what the device is called on the frontend-interface. The final field is an array of type "DeviceCapabilityStatus". A capability in this system represents something the device can do. This takes the form of a string. If a capability is available, that means the server relays that capability to any frontend devices connected to the server. If it is not available, the server still keeps that information, but does not relay it to frontends. Finally, a capability also has a type, which is how it is represented in the frontend. Currently, it can be shown as a button, or a slider.

A simple example of a capability is one for a lamp. A lamp could have two capabilities, "turn on" and "turn off", both being represented as buttons. If the lamp is off, the capability "turn on" is available to the user. If the user decides to invoke that capability, the lamp will turn on, the "turn on" capability will no longer be available and the "turn off" capability will become available. Finally, the lamp could have a capability called brightness, that controls the brightness of the lamp, this could be represented by a slider.

This system has much room for extension, with some glaring features that need to be added being:

- Access levels, only an admin can see this capability.
- Additional capability types, such as flip switches, or input fields

The device sends this registration request to the server. With the information from the request, the server can then register the device in a HashMap, which maps the device

UUID to the Device struct, following the steps described in figure 4.2. The Device struct is defined in */backend/src/server/device.rs* as:

```
1 pub struct Device {
2     pub name: String,
3     pub uuid: Uuid,
4     pub stringified_uuid: String,
5     pub active_capabilities: Vec<DeviceCapabilityStatus>,
6     pub inactive_capabilities: Vec<DeviceCapabilityStatus>,
7     pub device_public_key: rsa::RsaPublicKey,
8     pub device_verification_key: VerifyingKey<Sha256>,
9     pub certificate: String,
10 }
```

The structure of a device is quite self-explanatory, the only thing of note is having the UUID as two fields, one time as the UUID struct and once as a string. This is due to the type conversion being done very often in certain sections of code, it made sense to do this conversion once and reuse it. For information about the RSA keys and certificates present in this struct, view the section 4.4.

4.1.4 Device & Server Communication

Device and Server communication happens through polling. Every 0.5 seconds the device sends a request through the "RequestUpdateService" to the server. The service is defined in the */protos/iot/requestUpdateService.proto* file:

```
1 service RequestUpdateService {
2     rpc PollForUpdate(PollRequest) returns (PollResponse);
3 };
```

The "RequestUpdateService" has one function, named "PollForUpdate". It accepts a "PollRequest" as a parameter and returns a "PollResponse". When a device requests an update from the server, it must provide its UUID, certificate, a timestamp of when it was sent and the signature of the message, so the server knows what device is requesting and so the server can ensure that the device is who it says it is. Additionally, it provides it's updated list of capabilities. Below is some pseudocode to show how the server creates a response (you can view the real function in file *backend/src/server/polling.rs*):

```
1 def poll_for_update(self, request):
2     device = self.connected_devices.get(request.uuid)
3     if device == null:
4         return PollResponse(
5             has_update: PollingOption::DeviceNotFound,
6             updates: [],
7         )
8
9     signature_valid = verify_signature(device, request)
10    if signature_valid is not True:
11        return PollResponse(
12            has_update: PollingOption::InvalidSignature,
13            updates: [],
```

```

14         )
15
16     if !request.updatedCapabilities.is_empty():
17         active_capabilities, inactive_capabilities = (
18             request.updatedCapabilities.partition(
19                 (capability) => capability.available == True
20             )
21         )
22         device.replace_capabilities(
23             active_capabilities,
24             inactive_capabilities
25         )
26
27         self.frontend_cache_valid = false
28
29     updates = self.updates.get(request.uuid)
30     if updates.is_empty():
31         return PollResponse(
32             has_update: NONE,
33             updates: [],
34         )
35
36     updates_clone = updates.clone()
37     updates.clear()
38
39     return PollResponse(
40         has_update: SOME,
41         updates: updates_clone
42     )

```

When the `poll_for_update` function receives a request, it first checks if the device has updated capabilities. This can happen if something has changed with the device since the last poll or since registration. If the device has updates capabilities, then they are replaced and the frontend cache is invalidated. The frontend cache being invalidated means that some values need to be recalculated next time a frontend requests information about this device, instead of simply using the previous values.

Next the function checks if any events are available for the device in question. Events are created by the user on the frontend. For example, when the frontend activates capability "turn_on", an event is created on the server for the corresponding device. When the device then requests updates, this event is sent to the device and the device can respond accordingly. The server will include in the poll response, an indicator if new events are available, or an error code. If events are available they will also be included in the message.

When the client receives the response to their poll, they can then decide what to do with the events they have received, the server does not define any behavior. It simply reports to the client any events that have happened. This choice was made to enable a programmer to better define device behavior themselves and prevents issues with the server and device being out of sync about what behaviors are available. The downside of this, is that the server cannot guarantee to the frontend that anything has happened when a button is clicked. It also cannot give feedback until the event is processed by the

IoT device. Another downside is that it leads to more calculation being done on the IoT device itself and can potentially lead to lost updates if the device itself malfunctions.

4.1.5 Threads & Concurrency

write this

4.2 Device Library & Example Device

Another goal of this project was to create a library that can be used by other programmers, to easily create an IoT device that can connect to this system. This library was written for use with Rust. It is published within the Rust library ecosystem website, found at *crates.io*. The library entry on *crates.io* can be found [here](#).

4.2.1 Using the Library

The main purpose of the library is to abstract details of how the client & server connection works away from the programmer. While they can still view the source code due to it being open source, they should not need to know the inner workings of the library to be able to use it. The example below, which can be found within the repository for the example device [here](#), demonstrates usage of the library to create a simple IoT device. The purpose of this device is to toggle an LED, attached to a general purpose input output (GPIO) pin, on and off when the appropriate event is received. This code is made to run on a Raspberry Pi and will therefore not run on non Raspberry Pi Devices. It uses a combination of the NOSHP_Client library (the library created within this paper) and rrpal, a library commonly used to interact with the Raspberry Pi's GPIO in Rust. View the entire code for this simple IoT device and an in-depth explanation of it below:

```
1  #[derive(Default)]
2  struct ExampleState {
3      text: String,
4  }
5  impl UserDefinedState for ExampleState {}
6
7  const CONFIG_PATH: &str = "./example_config.toml";
8  #[tokio::main]
9  async fn main() -> Result<(), Box<dyn Error>> {
10     let config = ClientConfig::load_config(CONFIG_PATH)
11         .unwrap();
12
13     let client_handler = NoshpClient::new();
14     client_handler
15         .set_state(ExampleState {
16             text: String::from("hello world"),
17         })
18         .add_callback("Turn On", Box::new(turn_on_led))
19         .add_callback("Turn Off", Box::new(turn_off_led))
20         .run(config)
21         .await
```

```

22         .unwrap();
23
24     return Ok(());
25 }
26
27 fn turn_on_led(
28     _state: &mut ClientState<ExampleState>,
29     _req: Request
30 ) {
31     println!("Turn On")
32 }
33
34 fn turn_off_led(
35     _state: &mut ClientState<ExampleState>,
36     _req: Request
37 )
38 {
39     println!("Turn Off");
40 }

```

State

On line 8 the state struct of the program is defined. State will later be shared between callback functions. This can be defined by the user to fit their needs. The only requirement is that the user defined state struct must implement two interfaces. The first is called "State" and is imported on line 2 from the NOSHP_Client library (our library). This State interface is currently empty, it has no required functions, it exists to make future additions to the library easier to integrate. If it is decided that a function is required on the state struct, it can be easily added to the interface and the user will get a compile time error that is easy to understand. The second interface is called Default. It simply defines the default implementation of the struct, in this case constructing a new "ExampleState" (the name of our State struct), with the "led_pin" field set to the appropriate GPIO pin (defined on line 24), in this case where the pin the LED is connected to. This will then later be used by callback functions (view Callback Functions), to turn on the LED, without having to construct a new GPIO struct every time.

Configuration

Next we will have a look at the main function. On line 28 the configuration for the client is loaded from a file. This file is defined in a constant on line 25, under *./example_config.toml*. The configuration files for the client library are written in Tom's Obvious Minimal Language (TOML), a language often used in Rust projects. Its usage is similar to languages such as JSON or YAML (Yet another markup language). The configuration file looks like this:

```

1 device_name = "Pi"
2 server_ip = "http://192.168.0.0:2302"
3
4 [capability."Turn Off"]

```

```

5     available = true
6     type = "button"
7
8 [capability."Turn On"]
9     available = true
10    type = "button"

```

This configuration is loaded using the "load_config" method from our library, imported on line 3.

The Client Handler

On line 31, we finally construct the client handler, by calling the "new" method on the "NoshpClient" struct, imported from the Noshp_client library. Calling the new method initializes the variables inside the NoshpClient, including calling the default method on our State. This might be confusing to someone who is new to Rust, as we never informed the NoshpClient of the ExampleState struct. In this case Rust uses type inference, to infer what struct we are trying to use as our client's state. It infers this information from the callback functions we pass to it using the "add_callback" method, as they define one of their parameters to be ExampleState. If we were to remove these calls to add_callback, Rust would throw an error at compilation, stating that we need to specify the type of State. The definition of the NoshpClient looks like this (from *client_library/src/client.rs*):

```

1 pub struct NoshpClient<S: UserDefinedState> {
2     callbacks: FxHashMap<String, Box<Callback<S>>>,
3     client_state: ClientState<S>,
4     server_ip: Option<String>,
5 }

```

NoshpClient is a struct that accepts one generic argument, named S. S needs to implement the interface State (which in turn requires an implementation of the interface Default). NoshpClient has three fields:

- Callbacks - A hashmap used to map capabilities (stored as Strings), to user defined callback functions.
- Client State - Of type S, used to store the state of the program.
- Server IP - Of type option, stores either a string representation of the server's IP address and port, or None. It has the option type, due to there being multiple ways of giving the ClientHandler the server's IP address, however the client will not start if server_ip is None when the "run" method is called.

Once the NoshpClient has been constructed, we use the builder pattern mentioned in subsection 4.1.2, a very common Rust pattern. There are a few methods currently implemented on the ClientHandler, which we can call using this pattern. The most common one is the "add_callback" function. We use this to give the ClientHandler a pointer (signified by the "Box" struct in Rust) to our function, along with the capability (defined in the config.toml file) it should be called for. If no callback is added for a capability, a default function is added instead.

The NoshpClient struct has some other useful methods which the user can call. Some examples of these are:

- `Set_state` - Allows the user to set the state of the program to the non-default implementation. Can be useful if the state is determined programatically. This could allow the machine to change behavior at runtime. An example of this is having different behaviour depending on where the device is located.
- `Set_server_ip` - While the IP can simply be set in the config and read at runtime, it can instead of be passed using this function. This allows the user to programmatically determine the IP address, for example using network discovery to discover the IP address of the server, instead of using static IPs like in this example.

These methods can be useful, but are not required for using the library. Once all callbacks have been and other additional user parameters have been added, the `run` method is called. The `run` method accepts the configuration (obtained through the `load_config` function) for the device as a parameter and returns a future, which must be awaited using the `await` keyword (view subsection 4.1.5). This allows the `NoshpClient` to be used concurrently to any other tasks the client has to perform.

Callback Functions

Finally, the callback functions, used in the `"add_callback"` method on the `NoshpClient` are defined. The `NoshpClient` struct accepts callback functions, that must take two parameters and return void (defined as having no return value in Rust). The first parameter must be a Struct that implements the interface `State`, which the `NoshpClient` uses to infer the type of `State` in the above example. The second parameter must be of type `Request`. `Request` is a simple struct with one parameter, an optional float. This is useful if the capability is a slider, as the request parameter will contain the information about what value the slider had when the request was called. This can easily be extended in the future.

The functions in this case are very simple, they simply print a small statement about what they are intended to do. For example, if the frontend activates the capability "Turn On", then "Turn On" will be printed on the device side.

4.2.2 Device Registration

While device registration is described in detail within subsection 4.1.3, how the library handles registration on the client side will be briefly touched upon within this section.

While the code for client registration section is significantly more simple than that of the server registration, it has again been translated to pseudo code for consistency. The real code snippet can be found within `client_library/src/client_registration.rs`:

```

1 def register_self(
2     public_key,
3     capabilities,
4     device_name,
5     server_ip
6 ):
7     client = RegistrationServiceClient::connect(server_ip)
8     registration_request = new RegistrationRequest(
9         name, public_key, capabilities
10    )
11

```

```

12     response = client.register(registration_request)
13     return new ServerConnection(
14         response.client_id,
15         response.public_key,
16         response.certificate
17     )

```

The `RegistrationServiceClient` is the counterpart to the `RegistrationServiceServer` used by the gRPC server and is imported from the generated code from the `RegistrationService` protobuf file. We use the client returned by the "connect" method on the `RegistrationServiceClient`, to call the RPC function "register" (view subsection 4.1.1 for more information on how RPC functions are defined). This then returns the fields required for communication with the server. Finally, we return the `ServerConnection` struct which is a basic struct from the client library defined as:

```

1 pub struct ServerConnection {
2     pub uuid: String,
3     pub server_pub_key: rsa::RsaPublicKey,
4     pub security_certificate: String,
5 }

```

which stores information required for communication with the server.

4.3 Web & CLI Frontend

This section will describe how both the Web and Command Line Interface (CLI) frontends were implemented. It will also discuss specific struggles that were encountered when attempting to create these, and solutions or workarounds to these.

4.3.1 Command Line Interface Frontend

The first frontend that was implemented was the CLI frontend. It allows a user to control any IoT devices connected to the server from a simple command line environment. I was also very useful for testing purposes, as it allowed me to test that the system was working from a simple interface.

Running

Running the CLI frontend is fairly simple. After compiling the binary from Rust with the compiler in release mode, simply run the binary with the flag "`-server-address`" (short-hand is `-s`), inputting the gRPC address of the server as the `server-address` argument. This is made easy as the server outputs the address the gRPC server is running on at startup. For example:

```

1 $ ./frontend -s 192.168.0.1:2302

```

will run the frontend if the server's IP address is `192.168.0.1:2302`.

Using the Interface

Using the interface is quite simple. At startup the user will be greeted with two options:

```
1 Connecting...
2 Connection Successful
3 Welcome to Nik's Smart Home System
4 Your Device id is: 9404bec6-6a07-4374-bb34-f31e5809e348
5
6 What would you like to do?
7 1. Control a device
8 2. Quit
```

If they select *Control a device* (by entering the number 1), the frontend will fetch any devices connected to the server.

```
1 Fetching available devices...
2 0: Pi
3 1: Quit
4
5 What device would you like to control?:
```

Currently there is only one device connected to the server, with the name "Pi". If we select to control the "Pi", we will be met with the screen:

```
1 Heres what you can do:
2 0: Turn Off
3 1: Turn On
4 2: Quit
```

Under the hood, the frontend is fetching any capabilities defined within the config.toml being used by the device we are attempting to control. For more information how this works view section 4.2. If we select any of the capabilities, we will be met with the text:

```
1 Making request....
2 Operation was successful
```

If the request was unsuccessfully received, then an error message will be printed instead:

```
1 Making request....
2 There was an error:
3 status: Unavailable, message: "error trying to connect:
4 tcp connect error: Connection refused (os error 111)",
5 details: [], metadata: MetadataMap { headers: {} }
```

If the request was successful, then the next time the client polls the server, they will receive the event that selected and the callback function attached to that event will be called, in this case turning on or off an LED connected to the device. For more information on this view section 4.2.

Implementation

This section will give a description of how the CLI frontend functions and some design decisions made throughout.

The CLI frontend is relatively simple when compared to the rest of this system. All logic is contained in the file ***backend/src/frontend/frontend.rs***. It uses gRPC to communicate with the server, using the same gRPC server as the devices. In fact, any device could also act as a frontend and vice-versa. The frontend API is defined within

protos/frontend. For example, the definition for frontend definition is defined in *protos/frontend/registrationService.proto* and can be seen in appendix section B.0.3.

The frontend gRPC API has two functions, "Register" and "GetConnectedDevices". The Register function is used to register the frontend with the server. The frontend will then assign it an identifier, with which it can make requests. The GetConnectedDevices function is used by the frontend when the user requests connected devices. The server will respond with the device name, it's ID and any capabilities the device has. The server only responds with capabilities that are currently available.

4.3.2 Web Frontend

The web frontend was built using a combination of Typescript and VueJS. It mainly serves as a proof of concept, minimum viable product web-frontend, as it is expected that most users would build their own frontend for their own needs. It also serves to demonstrate how a user can access and use the frontend API to build a web frontend.

Running

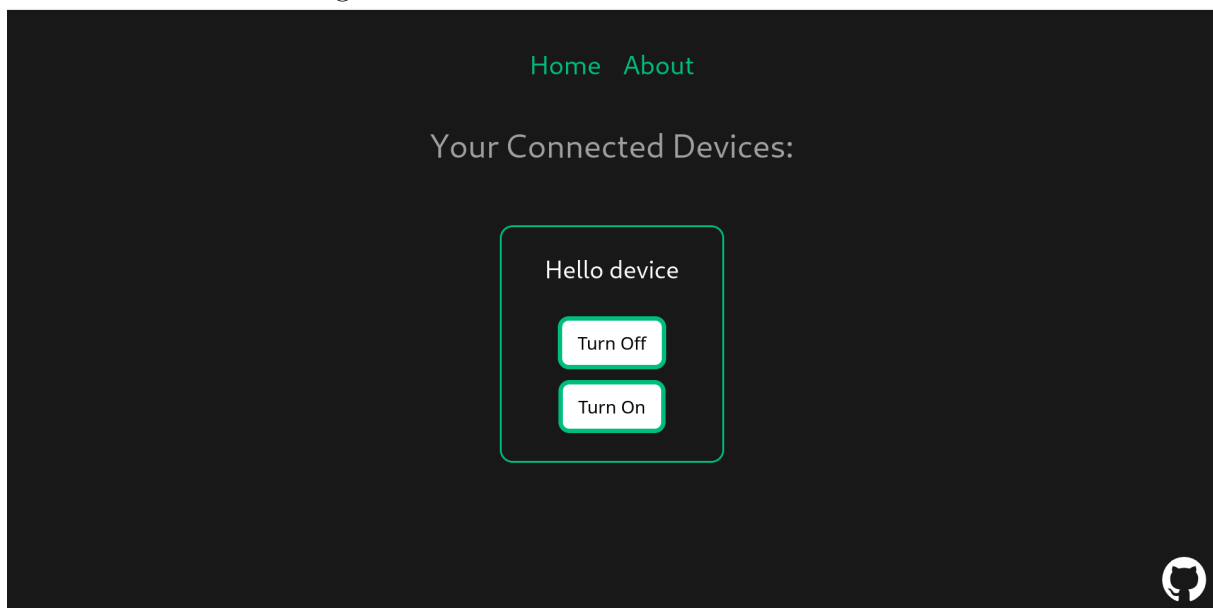
The web frontend can be run from the *vue_frontend* directory. Using the node packet manager (NPM), using the command: `npm install`. Once all dependencies have been installed, protobuf files must be compiled. This can be done using the bash script *vue_frontend/build_proto.sh*. From there the site can be hosted using: `npm run dev`, and can be accessed at `localhost:5173`.

Design

The final design of the frontend is fairly close to the original design proposed within figure 3.4. View figure 4.3 for the final design (note that for readability reasons it has been zoomed in considerably).

add a show-case of the slider to this screen shot as well

Figure 4.3: Web-frontend Home Screen Final



The designs look fairly similar, with the only real difference being Github icon in the bottom right corner, that serves as a link to the project's repository. This allows the user easy access to documentation, or the ability to file a bug report in the Issues section of the repository.

Calling the frontend API from the Web

There are two ways to call the frontend API, one through JSON using an HTTP server, the second through gRPC. For the reasoning behind this view subsection 4.3.3. The web-frontend uses the JSON API to make calls to frontend API endpoints. All this means for a user of the system, is that they will need to start the server with the *"--json-frontend"* flag, to enable the HTTP server that allows for JSON calls.

Once the HTTP server has been enabled, calling the frontend API is fairly easy. The `vue_frontend` (which houses all web frontend files) contains a simple script which can be used to generate JS files and with Typescript type definitions from the protobuf definitions. The script uses a Javascript library called `ProtobufJs`, to generate these files. Once these files are available, all types used in the CLI frontend are now also available, making calling the frontend API very easy. A typescript code snippet that shows how calls can be made to the JSON Proxy server can be seen in appendix section B.0.4.

In this typescript snippet we construct a new `"RegistrationRequest"`, which is defined in the protobuf definition file from section 4.1.1, send it in the JSON format to the server. We then await a response and parse it into a `"RegistrationResponse"` and return that. The request is being made to the address `"http://localhost:5173/api/frontend/registration"` (defined in a constant, not visible in example). While at first this seems strange, as the JSON proxy is being hosted on address `"http://localhost:2302"`, however due to the `"/api"` prefix in the address, the request is automatically forwarded to the HTTP server. This is handled by the Vite web server, which is hosting the website, which is being run when we call `"npm run dev"`.

4.3.3 Using JSON for the Frontend API

Throughout this report a JSON frontend API has been alluded to, this subsection will explain why it was necessary to implement this in the first place. gRPC uses the HTTP/2 protocol to communicate, which is supported by web browsers. However, some features in HTTP/2 required by gRPC are not exposed by web browser [2] for a variety of reasons, which lead to the creation of gRPC web. gRPC web functions slightly differently to normal gRPC and is not compatible with normal gRPC, due to the aforementioned HTTP/2 issues. Because of this, a proxy between the normal gRPC server and gRPC web needs to be used to communicate.

Instead of using a separate program as a proxy, I decided to use a JSON to gRPC translation proxy instead, running on the server. This makes it possible to use a web-based frontend, without having the additional restrictions imposed by gRPC web. The downside of this, is that another HTTP server needs to be spawned, if the user decides to use JSON. Additionally, all benefits of using gRPC with the frontend are lost, as JSON is sent anyway. That being said, there are some benefits.

The JSON proxy I have created is completely transparent to the server, as the proxy calls gRPC functions. Additionally, the protobuf files are still used in combination with Typescript. This means that nothing in the packets is changed between the proxy and the server, the packet is simply parsed and forwarded as a gRPC packet. Another positive side

effect of the JSON proxy, is that most frontend developers are significantly more familiar with working with JSON than gRPC, making it easier to create a custom frontend for the system. No extra program needs to be installed, or started when using a web-based frontend, one simply needs to include a flag when starting the server and the rest is handled automatically. Finally, if a user wants to create a web frontend using gRPC web, this can easily be done, with no changes required to the server code.

View an example below of how JSON calls to the server are translated to gRPC function calls (from the file *backend/src/server/web_json_translation/json_registration.rs*):

```

1  #[actix_web::post("/frontend/registration")]
2  pub async fn json_registration(
3      req_body: String,
4      state: actix_web::web::Data<TranslationClientState>,
5  ) -> impl Responder {
6      let parsed_req:
7          json_registration_service::RegistrationRequest =
8          match serde_json::from_str(&req_body) {
9              Ok(r) => r,
10             Err(_e) => return
11                 HttpResponse::BadRequest()
12                     .body("Unable to parse request"),
13             };
14
15     let response = {
16         let mut registration_service_client
17             = state.registration_client.lock().await;
18
19         registration_service_client
20             .register(parsed_req).await
21     };
22
23     let response = match response {
24         Ok(r) => r.into_inner(),
25         Err(e) => return HttpResponse::InternalServerError()
26             .body(e.to_string()),
27     };
28
29     return HttpResponse::Ok()
30         .body(serde_json::to_string(&response).unwrap());
31 }

```

While this code looks complicated (partially due to formatting restrictions), it is actually quite simple. We parse the JSON request into a `RegistrationRequest` struct. If fails we send an error to the sender. We then forward the request to our "registration_service_client", which is a gRPC client registered as a frontend with the server. This is contained in a `Mutex`, due to the fact that it may be accessed concurrently, so we need to wait for it's lock to be available first. Finally, we check that the response is not an error. If it is not, we turn the response to a string and forward it to the sender, otherwise we forward the error message.

4.4 Security

This section will briefly showcase implementations of the protocols described within subsection 3.3. Both certificates and signatures are using an RSA key-pair generated by the Rust RSA library specifically the Probabilistic Signature Scheme (pss) module. From the private and public key we can generate a signing and verification key respectively. These are then used to sign and verify the certificates.

4.4.1 Certificates

Generating certificates is fairly simple, the code for this can be found in the file *backend/src/server/certificate_signing.rs*. We use the server's signing key to generate a digest of csr (described in section 3.3). We then store this certificate on the server side and send a copy to the device requesting to connect. To verify a certificate we simply use the verify function, present on the server's verification key.

4.4.2 Signatures

Signatures are similarly simple. To generate a signature for a message being sent we use the sign_data function (from *backend/src/server/certificate_signing.rs*):

```
1 ///returns the signature and timestamp of the signature
2 pub fn sign_data(&self, data: String) -> (Vec<u8>, u64) {
3     let timestamp = get_timestamp();
4     let data = timestamp.to_string() + &data;
5
6     let mut rng = rand::thread_rng();
7     let signed = self.signing_key.sign_with_rng(
8         &mut rng, data.as_bytes()
9     );
10    (signed.to_vec(), timestamp)
11 }
```

As mentioned in the comment on line one, this function takes data in the form of a string, concatenates it with the current time-stamp (in Unix time), then signs it with the same pss signing key used to generate certificates. It then returns the signature in the form of an Array of bytes, along with the timestamp.

Due to more complexity in the verification function, it will be provided in pseudo code. For the original Rust code, view the file *backend/src/server/certificate_signing.rs*.

```
1 def verify_signature_update_request (
2     client_verifying_key,
3     certificate,
4     updated_capabilities,
5     client_timestamp
6     signature
7 ):
8     server_timestamp = get_timestamp()
9     if (
10         server_timestamp - client_timestamp
```

```

11         > SIGNATURE_EXPIRATION_SECONDS
12     ):
13         return false
14
15     capability_string = updated_capabilities.reduce(
16         (acc, capability) => {
17             acc + capability.to_string()
18         }
19     )
20     to_check_against = client_timestamp
21         + capability_string
22         + certificate
23
24     return client_verifying_key.verify(
25         to_check_against,
26         signature
27     )

```

The signature verification function uses the client's verification key, derived from the client's public key, to verify that the signature is genuine. Included in the signature is the time the message was sent (view sections 3.3) The current expiration time for a signature (and in extension a message) is 10 seconds. This ensures that an attacker cannot use a replay attack to maliciously control the system and if something goes wrong during packet transfer, that outdated packets don't influence behavior.

5 Testing & Evaluation

This chapter will provide details on functionality and performance tests carried out on the completed system and will provide some analysis of results gathered through these.

5.1 Using the System

Tests within this section will test the actual functions of the system. It will go over different features of the system and check that they all work as intended.

For all tests in this section a Raspberry Pi 4b was used to host client code, running Raspberry Pi OS Lite (with no desktop environment), which was released on December 11th 2023. The server and frontend were hosted on a Laptop with an Intel i5-12450H processor, running Fedora 39 Linux. The Raspberry Pi's hostname (visible in screenshots) is "nikpi".

5.1.1 Controlling one connected device

Perhaps the most obvious and basic test is to create a device, using the Rust client library, have it run on a device and to connect with that device to a running server.

Testing Setup

A simple client was created, with two capabilities "Turn On" and "Turn Off". The callback functions attached to these capabilities would simply log to the standard output the name of the capability they are attached to. The Raspberry Pi is connected to the same Wi-Fi network as the server. The port 2302 has opened on the laptop's firewall to ensure the Raspberry Pi can make requests to the gRPC server. The Raspberry Pi is being controlled through a secure shell connection (SSH) (visible on the left side of screenshots). View figure 5.1 for the exact configuration of the client.

Testing

Figure 5.2 shows the successful connection and certificate exchange between the client on nikpi and the server. Note that the server ip that the client is connecting to is set within the client's configuration file (view figure 5.1). In this case the server (on the right side of figure 5.2) is being started with the "json-frontend" flag, as discussed within subsection 4.3.3, this flag is required to use the web-based frontend.

The next important test is viewing the web frontend, to see that the device is correctly displayed on the frontend, with the appropriate capabilities. This can be seen in figure 5.3, where the device, named "Hello device" (view configuration file) can be seen with it's two capabilities "Turn Off" and "Turn On". The web-frontend is being hosted by a Vite server, through using the command "npm run dev", on localhost port 5173. The frontend is being rendered by the Chromium web browser.

Figure 5.1: Client's configuration file

```
nik@nikpi:~/dev/test_client_lib $ cat example_config.toml
device_name = "Hello device"
server_ip = "https://192.168.167.110:2302"

[capability."Turn Off"]
    available = true

[capability."Turn On"]
    available = true
```

Figure 5.2: Establishing a connection

```
nik@nikpi:~/dev/test_client_lib $ ./target/release/test_client_lib
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection

+ backend git:(main) x cargo run -r --bin server -- --json-frontent
Finished release [optimized] target(s) in 0.06s
Running `target/release/server --json-frontent`
Started GRPC Server on 192.168.167.110:2302
Starting JSON API Layer...
[2024-03-09T09:32:56Z INFO actix_server::builder] starting 12 workers
Successfully Started JSON API Layer on localhost:50052
[2024-03-09T09:32:56Z INFO actix_server::server] Tokio runtime found; starting in existing Tokio runtime
```

The final test for this subsection is to attempt to trigger the two listed capabilities, by clicking the buttons. This should send a JSON packet to the JSON proxy server, which is then forwarded to the gRPC server. Once this request has been processed, the server will add it to the list of updates for the specified client. The client will then eventually poll the server and receive the update. It will then call the callback function associated with that capability. For this specific test both buttons will be clicked, starting with the "Turn Off" button, then the "Turn On Button". As shown in figure 5.4 this works as expected and the associated callback functions are called.

You can view the complete code for the client used in this example in the appendix in appendix section B.0.1. Due to the simplicity of setting up a client using the NOSHP-Client library, its only 47 lines long.

5.1.2 Controlling multiple connected devices

This section will be a continuation of the last section, except that multiple devices will now be run, instead of just one. One device will still be run off the Raspberry Pi, the other devices will be run locally, on the server. They will however still be connecting to the public IP Address, not the loop-back address. Running them on the same device as the server has potential performance implications, however it is not relevant to this section, as we are simply attempting to test the functionality of the system.

Testing

One slight modification has been made to the client code in appendix section B.0.1, a print statement has been added to the main function, which prints the device name to standard output. This aids in clarity for which device is which in the screenshots. Additionally,

Figure 5.3: Web Frontend with the connected device

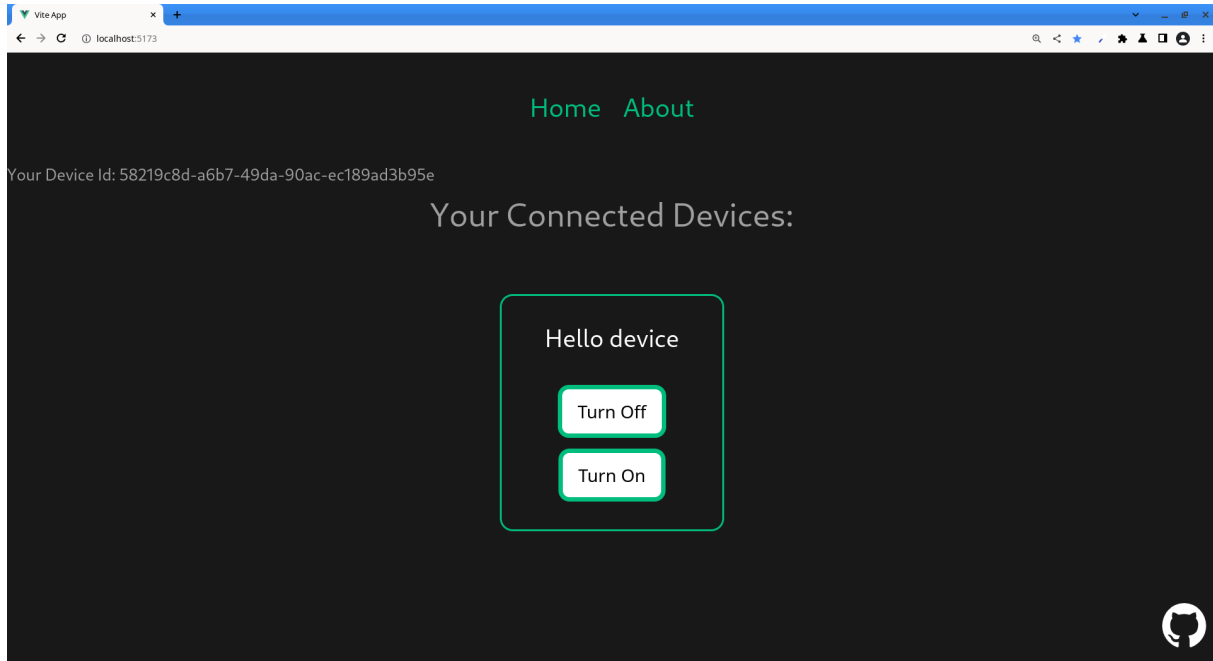
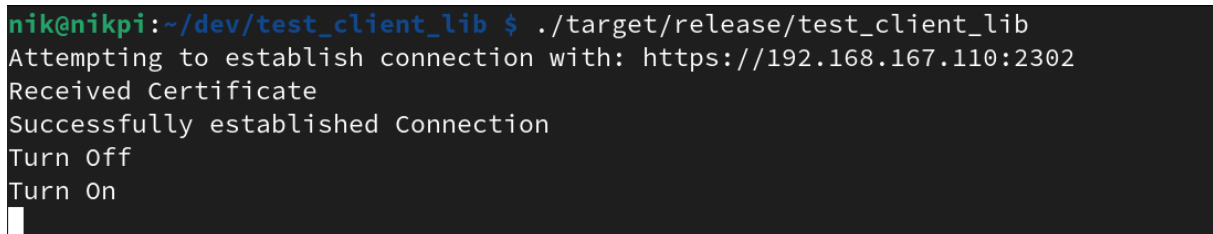


Figure 5.4: Triggering capabilities



configurations have slightly changed, with each device having uniquely named capabilities and device names, to demonstrate the frontend's ability to show different devices. The IP address they are connecting to will stay the same (the server's IP printed at startup).

As seen in figure 5.5, connecting four devices the server is no problem. All four connect, receive their certificate and print that they have successfully established their connection. The next test is to see that all are displayed properly on the frontend, with the correct device names and capability names.

Figure 5.6 shows all four devices, with their correct names and capabilities displayed on the web frontend. Note that nothing has been changed about the frontend during this time, this has all been dynamically changed due to changing connected devices. Finally, we must test controlling each of the four devices. This was done by clicking every button seen on screen, from left to right and top to bottom order. The results from this can be seen in figure 5.7.

All four devices trigger their capabilities correctly. That being said, a potential issue was uncovered during this experiment. Due to latency between server and device (specifically the Raspberry Pi which was connected through Wi-Fi), packet signatures can expire before they reach the device. This can lead to lost information, as the server has already

Figure 5.5: Establishing Connection with four devices

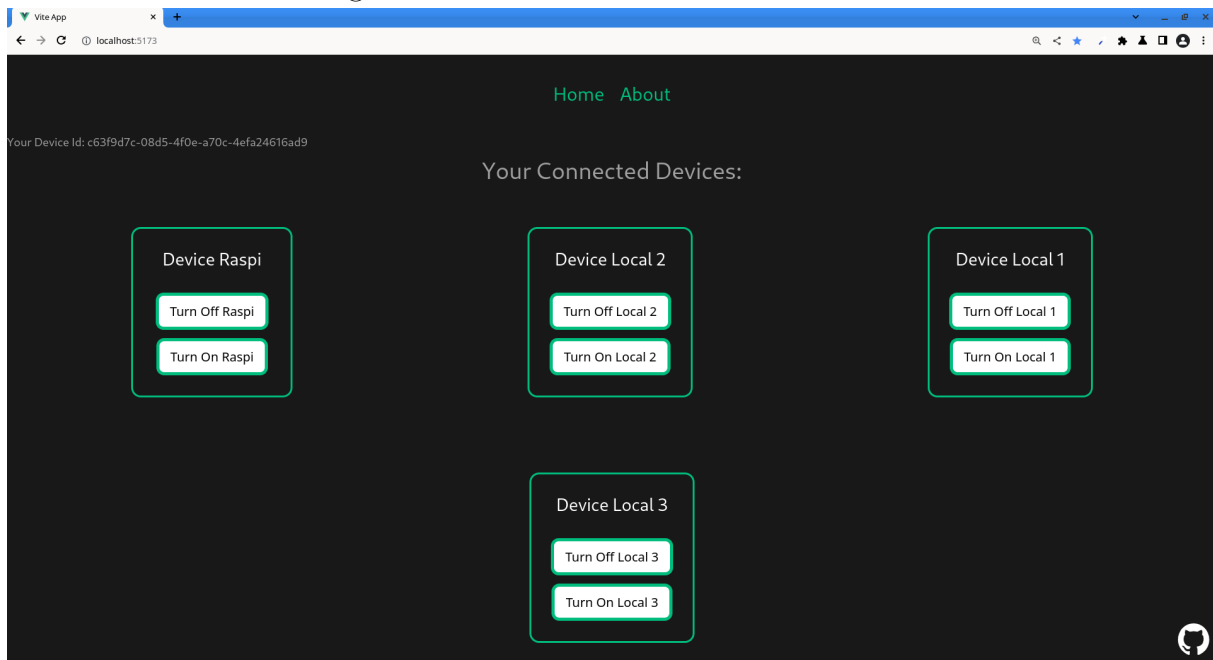
```
tmux
nik@nikpi:~/dev/test_client_lib $ ./target/release/test_client_lib
Device: Device Raspi
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection

+ dev_1 git:(master) x
+ dev_1 git:(master) x ../target/release/test_client_lib
Device: Device Local 1
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection

+ dev_2 git:(master) x ../target/release/test_client_lib
Device: Device Local 2
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection

+ dev_3 git:(master) x ../target/release/test_client_lib
Device: Device Local 3
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection
```

Figure 5.6: Web-frontend with four devices



removed the update. While a somewhat rare problem, it could happen frequently on a faulty connection. An easy fix was to increase the amount of time it takes for a signature to expire, however a proper fix would for the client to send a response message, when the update has been received. The server would only delete updates when this message is received.

5.2 Performance Testing

The main metric that was interesting for performance testing was the amount of clients the server can handle, connected at once. A secondary objective was testing the performance of the client.

Figure 5.7: Triggering capabilities with four devices

```

tmux
Device: Device Raspi
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection
Received signal to Turn Off Raspi
Received signal to Turn On Raspi

+ dev_1 git:(master) x
+ dev_1 git:(master) x ../target/release/test_client_lib
Device: Device Local 1
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection
Received signal to Turn Off Local 1
Received signal to Turn On Local 1

+ dev_2 git:(master) x ../target/release/test_client_lib
Device: Device Local 2
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection
Received signal to Turn Off Local 2
Received signal to Turn On Local 2

+ dev_3 git:(master) x ../target/release/test_client_lib
Device: Device Local 3
Attempting to establish connection with: https://192.168.167.110:2302
Received Certificate
Successfully established Connection
Received signal to Turn Off Local 3
Received signal to Turn On Local 3
  
```

Additional Programs

Gnome's "System Monitor" was used during the testing process to monitor resource usage of the server. Window's "Task Manager" was used to view the client's resource usage.

Two simple programs were constructed for this testing process. The first is a mock frontend. This frontend's Job is to act as a sort of distributed denial of service attack (DDOS) on the server, attempting to generate as many requests in a short amount of time as possible. To do this, it requests all connected devices and their capabilities. It then iterates through every connected device and sends a request to trigger all available capabilities. It repeats this process multiple times, with the amount being determined by an argument passed to the program, which is called "count". If the server has 10 clients connected to it, with two capabilities each, with the DDOS' count variable being set to 100, then $requestAmount = 10 * 2 * 100 = 2000$. All these requests are sent as fast as the server will accept them. Each request also carries a timestamp with it, of when it was sent. This can then be measured against when the server forwards the request, to find the time it took for the server to receive, process and forward the request. These requests are sent through gRPC, so there is no added delay from the JSON http-proxy to take into account. View the code for this DDOS attack below (from *testing/ddos_noshp_server/src/main.rs*):

```

1     println!("Starting DDOS Attack");
2     for _ in 0..args.count {
3         println!("finished iteration");
4         let devices =
5             get_connected_devices(
6                 &device_id,
7                 &mut registration_client
8             )
9             .await
10            .unwrap();
11
12        for device in devices.iter() {
13            for capability in device.capabilities.iter() {
14                if capability.available {
15                    control_client.control_device(
16                        DeviceControlRequest {
  
```

```

17         capability: capability
18             .capability.clone(),
19         device_uuid: device
20             .device_uuid.clone(),
21         timestamp: get_timestamp(),
22     }
23     ).await.unwrap();
24 }
25 }
26 }
27 }
28 return Ok(());

```

The second program written for these tests is a simple client implementation, that uses the `NOSHP_client` library to spawn clients, each running on its own thread. It will spawn the amount of clients specified through a command line argument, stored in the "count" variable. View the code for this second program below (from *testing/spawn_noshp_clients/src/main.rs*):

```

1 for i in 0..args.count {
2     let mut config = config.clone();
3     config.device_name += &i.to_string();
4     let handle = tokio::spawn(async move {
5         let client_handler = NoshpClient::new()
6             .add_callback("Turn On",
7                 Box::new(turn_on_led))
8             .add_callback("Turn Off",
9                 Box::new(turn_off_led))
10            .run(config)
11            .await
12            .unwrap();
13    });
14    thread_handles.push(handle);
15 }
16
17 for handle in thread_handles {
18     handle.await.unwrap();
19 }

```

Testing Methodology

The clients and server were separated between two computers. This decision was made to ensure fair results. The server was run on a laptop, with an Intel i5-12450H processor, 16 GB of memory and running Fedora 39 Linux. The laptop was plugged into power and was set to performance mode. Clients were run on a desktop, through a Windows sub-system for Linux 2 (WSL2) installation of Ubuntu 20.04 LTS. The desktop had an AMD Ryzen-7700x processor at stock settings, with 32 GB of memory. WSL2 had access to all 16 logical processes (8 cores) and 16 GB of memory. The laptop and desktop were connected through a 100 Mb/s Wi-Fi connection.

The main metric that was being measured during this testing process was the processing time of the server. How long, on average, would it take for the server to process a request from the frontend under different loads? To test this, the time a request was sent from the frontend was taken, which was then measured against the time the request was forwarded to the client.

An important factor to keep in mind during this experiment was the polling rate of the client. A client will poll the server for new updates every 500ms, meaning that even if the time to process a packet is 0ms, the average response time of the server would still be 250ms, as the packet does not send the request until polled by the client. This means that optimal results from this experiment should trend towards that average, with anything above 250ms being of concern.

Test Setup

Five amount of clients were tested: 1, 10, 100, 500 and 700 clients connected to the server simultaneously. More than this were also attempted, however at above 700 clients the desktop's Linux operating system stopped being able to spawn new clients, citing OS error 24 "Too many open files". View appendix section B.0.2 to see an example of the error. It was therefore decided that 700 clients would be the upper limit of this test. That being said, 700 clients is far more than what will likely be connected to the system at one time. Each client in this test had two active capabilities, which would print to the standard output.

To simulate a high server load, the program simulating a DDOS attack (described above) was used. This program ran with 100 iterations for every number of clients, triggering each of their two capability. Each client would therefore have 200 requests, as fast as the server could receive them. Keeping the iterations the same for every run gave an advantage to the smaller number of clients, as not only did the server have to deal with fewer clients, but also less total requests. That being said it is a worthwhile trade-off, as this is mainly a test of how many requests the server can handle, before slowing down. The number of clients mainly has an impact on memory usage, not on performance. In this case that main way of scaling requests was simply to increase clients. Additionally, it also gives the server an advantage, due to the way the server code is written. Each client can be accessed independently, at the same time (by multiple cores or threads). However, due to the use of mutual exclusion, each client could only be accessed from one thread at a time. So having more requests, with less clients, would actually have a larger impact on server performance than the other way around.

Results

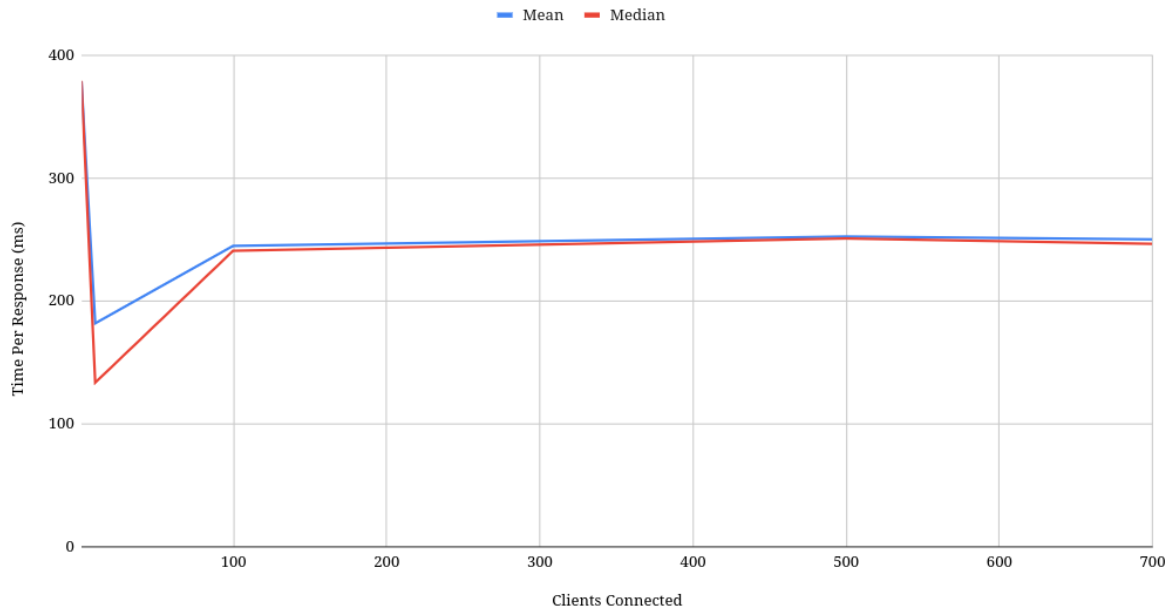
Table of Test Results:

Clients / Total Requests	Mean Response Time (ms)	Median Response Time (ms)
1 / 200	378.3333333	379
10 / 2,000	181.6666667	133.3333333
100 / 20,000	244.6666667	240.6666667
500 / 100,000	252.3333333	250.6666667
700 / 140,000	251	247.3333333

Each test was run a total of three times, the mean of all three results were taken as the value for each amount of clients. All experiment results can be found in the testing folder of the repository, along with scripts for calculating mean and medians of the files.

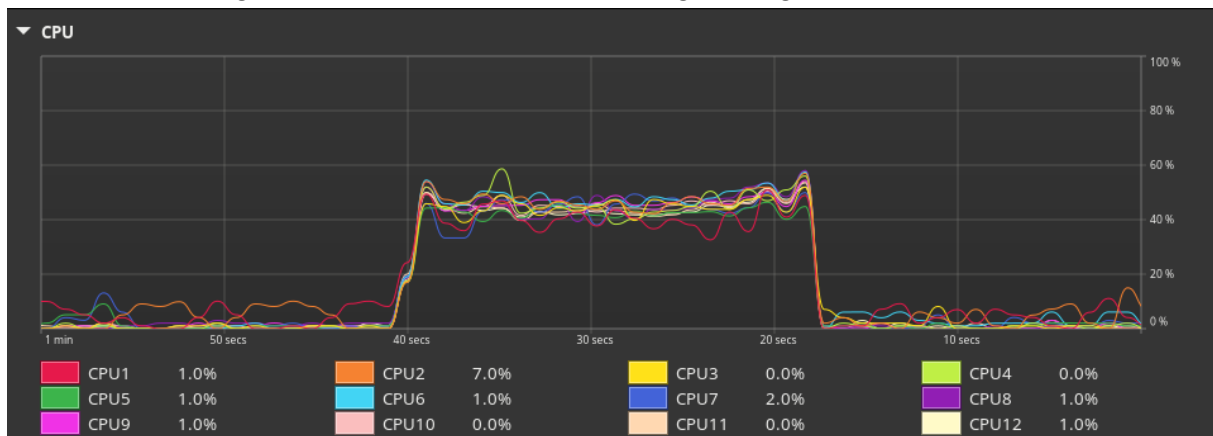
Figure 5.8: Performance Test Results Charted

Time between Frontend sending request and Client receiving it during maximum server load with every client polling every 500ms



As described above, the expected mean response time was 250ms, due to the 500ms polling rate. This is clearly reflected in the data, with the larger amount of clients trending the number. Especially the tests with 100, 500 and 700 clients there is a clear trend towards that value, with the tests with 1 and 10 clients having a very small sample size of clients, that could influence these results. That is most likely why the average response processing time of one client was the longest, due to when the one client polls the server in relation to when the request was sent massively influencing these results. What this result for one client most likely means, is that on average it polled for updates 378.3 ms after a request was sent.

Figure 5.9: Server CPU load during testing with 700 clients



These test results clearly show that 700 clients are not enough to create a significant enough load on the server, that it would start struggling to process packets. This is a good result, as the server is running on mid-range, laptop hardware. Additionally, realistically very few users of the software would have a need of 700 clients running on the server, especially while receiving 140,000 requests (that's nearly 7000 requests per second, seeing as the test took just over 20 seconds to run). It however does give a good indication of how the software might run on less powerful hardware.

Figure 5.9 shows the CPU load during the test with 700 clients. There is a significant spike around -40 seconds, when the requests started to flood in, then the load decreases again around -18 seconds, when the server is done processing the requests. Here we can see that all CPU cores/logical processes are under load during this time, which means the concurrent handling of requests is working as intended. We can also see that the maximum load it reaches is under 60 percent. This indicates that there is still room to add more clients, especially if one factor is in that server is also simultaneously running the DDOS attack, which would create additional load. These values were captured using the Gnome "System Monitor" application.

5.3 Conclusions from Testing

One major issue was discovered while performance testing the server. The simulated clients were run on a different machine than the usability testing, for performance reasons. Specifically, this machine was running the Windows operating system. While the server accepts Unix time-stamps as timestamps, which means timezones should not matter, the time on individual machines can vary by milliseconds, to a few seconds, simply due to clock drift. Due to this fact, the Windows computer's clock had drifted into the future by milliseconds which lead to the time check not working for signature checks. As the client's time was ahead of the server's time, this lead to the simple calculation to check a packets age to return negative numbers, marking every packet as invalid. The performance tests were run with this time check disabled. This issue has since been fixed, by taking the absolute value of the difference in times, meaning the time check should work, even with slightly mismatched times.

Overall, testing was a resounding success. During performance testing, the client software was able to build first try, with no tinkering, on a machine that had never run it before. The machine was able to connect to the server with no changes needing to be made, even though it was a Windows machine (the client was however running through WSL2). Performance results are very good, with headroom on the server to accept more than 700 clients and thousands of requests per second, even on a mid-range laptop processor. Usability testing showed that the web frontend and client works exactly as expected, with multiple clients, from different sources, being able to connect to the server at one time.

6 Discussion & Conclusion

6.1 Review of Aims

1. **Build a Server with an API for the smart home devices to communicate with.**

This was the main goal of this paper. Throughout the process of this project, a smart home server was created, which has three APIs. One for devices to communicate with and two for frontends to communicate with. This server accepts device requests to connect, allows these devices to advertise their currently available features/capabilities and allows a frontend to request control of these capabilities. It then forwards these requests to devices. Additionally, it provides security features, such as certificates and signature signing, to verify that devices are who they say they are. This server is performant enough to handle hundreds of clients to connect and receive requests at once, even on midrange hardware.

2. **Create a Library and API for building smart home devices.**

After creating a server for devices to connect to, a generalized Rust library was created, which allows programmers to easily create their own smart home devices and connect them to the server. This library also provides documentation for how to use it and is published on the official Rust library database. Additionally, an example IoT device was also built using this library, to provide developers a starting point and give an example of how to use the library.

3. **Create a frontend which will allow for control of devices connected to the system.**

Throughout this project two frontends were created. One of these, also programmed in Rust and using gRPC, allows for control of devices through the commandline. This was often used during the beginning of the project, as it allowed me to quickly test new features and iterate quickly. The second is a web-frontend, which allows the user to control the server through the browser. This was created once the server functionality was more complete. The web and CLI frontend have feature parity, however both are supposed to serve more of a guide on how to use the two different APIs (gRPC and JSON + HTTP), only providing required functionality (such as device control), while missing features a real user might want, such as access control.

4. **All code should be hosted in a public repository, with documentation for how to build and use every component of the system.**

While documentation is not as detailed as it could be, all code is hosted in a public repository, with instructions on how to build and run all components of the program. Additional focus was put on documentation of the client library/API, as this is the main piece that other programmers are expected to interface with. An example client was even created to help developers interface with the library.

6.2 Future Work

While this project is finished in terms of the aims of this report, it is far from done from an end-users perspective. There are some important, somewhat basic, features missing, such as access control, allowing device reconnection on connection loss, and general device features. However, in my eyes, the most important future work would be to audit and strengthen security measures. While the certificates and signatures currently implemented are a good start, the reality is that implementing a truly robust security system is not only out of the scope of this report, but also not plausible for someone with fairly little knowledge in system security to implement correctly. It is for this reason specifically that this smart home system is not ready for real life use, even if the feature-set is mostly ready. If the security measures could be audited and improved by a security expert, then this system would truly be ready for real-life adoption.

6.3 Concluding Remarks & Learning Outcomes

This project has been incredibly educational in a multitude of aspects. Working in a multithreaded, low level systems' language to build a real project taught me a lot about the importance of Mutual Exclusion and optimization through Read/Write locks. Interfacing with multiple libraries, in both Rust and JavaScript, gave insights on reading documentation and using other people's code. Working with multiple devices, communicating over a wireless network, while sometimes frustrating, taught me a lot of important networking knowledge. Simply working on the same project for months, with no instructions or predefined goals, apart from those I set myself, was a learning experience in itself, that I have not really been able to experience throughout my time at university. I cannot begin to list all the things that I have learned throughout this process.

In conclusion, while this project has areas that it can be improved upon, it was largely a success. I personally learned a lot and grew as a developer throughout the process and produced something that I can be proud of, while gaining knowledge that will surely carry on into my future career.

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A Original Project Proposal

An IOT connected Solid Waste Sorting System

A Project Proposal by Niklas Harnish

Abstract

In today's world of rapid consumption, plastic waste has become more of a problem than ever. That is why this project is setting out to build an open-source IoT system, with a plastic classification module. This IoT system will be a platform for other developers to build on, and will be able to collect and display data from the plastic classification module.

1. Introduction

This project proposal is split into six parts. The background section contains an analysis of software/projects that aim to do similar things to this project. Their strengths and weaknesses are then listed. The motivation then contains information on gaps within current systems that can be improved upon, or that don't fulfill the needs of a certain market. Within the scope section the aims and goals of this project are described, and perhaps more importantly, what this project **does not** want to be is also described. These are then expanded into formal functional and non-functional requirements, within the next section, requirements. Next comes methodology, where different technologies that are to be used, and the method of feedback collection is described. Finally, a formal timeline with some analysis on important steps throughout the project is given, along with a Gantt chart for clarity.

2. Background

With global plastic production at an all-time high (390 million metric tons in 2021 [13]), plastic sorting has become more and more important. At the same time, the average customer can not distinguish between different types of plastic and even if they could, the likelihood of customers being willing to have a different bin for each color, or type of plastic is low. As the world grapples with the consequences of the plastic waste generated through our ever increasing consumption, the need for a smart and connected system that requires little user intervention increases. However, plastic classification software and hardware often comes at great (monetary) cost.

The AUTOSORT FLAKE (AS Flake), created by the Norwegian for-profit company Tomra, is a high-performance flake sorting system. It can sort *“all kinds of polymers, including silver and white, as well as wood and paper”* and for metals *“all kinds including non-ferrous*

metals” [5]. With a plastic sensor resolution of 2 mm and metal sensor of 1 mm it can detect very small flakes. However, due to the proprietary nature of this product, there is not much publicly available information on both the capabilities or the price of the AS Flake, however it can be assumed by the size and industrial applications of this device that it is quite expensive. This will hinder many potential customers from buying it, it is only really useful within an industrial setting.

In contrast the *Plastic Scanner* is an open source plastic classification project, with instructions on how to create the hardware and to build and install the firmware hosted on GitHub[8]. The project is currently still in development, with the website stating that it is not ready to be used and should not be built unless seeking to help develop the product [9]. However, once in a production ready state, they promise to be able to identify five different types of plastics using a small handheld device. Internally, the device uses “*discrete near-infrared (NIR) spectroscopy*” [10] to identify plastics. Additionally the website has precise instructions on how to contribute to the project. While the Plastic Scanner is a great project, as mentioned it is still in development and also has a more niche application, mainly being used for handheld plastic identification. It is missing some automation features that might make it more generally useful.

OpenSpecy, described by Analytical Chemistry as open-source software that “*allows users to view, process, identify, and share their spectra to a community library*”. [11] These processed spectra can then be used with other programs. As described above with the *Plastic Scanner*, spectroscopy is often used to identify plastics, making this a valuable solution for this step in plastic classification. While the program can be used online, it also has a library which can be used with the popular statistical computing language “R”, to process spectra programmatically. However, it is not clear if these spectra are processed locally, on the user’s computer or within a server hosted by OpenSpecy. OpenSpecy has an open-source repository, hosted on GitHub, which describes the process of installation and using the program. [12] Theoretically any developer could use open-specy to create whatever plastic classification system they want. However, it is simply a small (but very important) part of plastic classification and a system has to be built around it. This requires a great deal of knowledge and expertise, in both spectroscopy and in software development.

The *Home Assistant* is an open-source smart home system that focuses on “Local Control and Privacy” [1]. It lets the user add their existing smart home products, from reputable brands such as *Phillips Hue* and *Sonos* [2], to a single interface. With 2569 integrations [2] many users will be covered by their supported products. Additionally, there is extensive documentation on how to install the software on the user’s devices, with a range of supported options, such as on a Raspberry Pi, or within a Docker Container [3]. All the code for this project is available on a public *GitHub* account [4], with clear guidelines for contributing listed in the documentation [3]. This issue with this project is that it is meant to integrate with existing technologies, with developing for the platform being a secondary objective.

The proposed project will aim to create two separate, but connected systems. The first is an open-source platform for building IoT modules. This will also include a hub, to connect these

modules and an easy to use frontend for easy control by the end user. Along with this, documentation will be provided, so developers can replicate and expand the module ecosystem, or develop on top of the foundations built by this project. The second is an open-source, IoT connected plastic classification device, that can be used to collect data and distinguish between different plastics.

3. Problem statement

As briefly mentioned above, the existing solutions have some issues that leave a gap in the market. While Home Assistant is a good project for people interested in connecting their existing smart home devices, it is not meant as a platform to build on top of. While the AUTOSORT FLAKE provides a good experience to those that can afford, and have space for the device, it is not a good solution for normal people interested in doing their part. The Plastic Scanner is a good solution, but is not ready for use and does not have some required automation/interconnectivity features. Finally OpenSpecy is simply a tool for plastic analysis, it does not provide much of the infrastructure to actually use it.

Cause	Effect
<ol style="list-style-type: none">1. No open source IoT system for knowledgeable people to build on2. Current solutions meant to integrate with existing, proprietary devices3. Plastic classification/sorting devices have high associated cost and space requirements4. Commercial Plastic classification/sorting devices use a lot of space5. Open-source classification software is still in development, no available product6. Open spectrometry software is available, however not in a complete classification package	<ol style="list-style-type: none">1. Lack of interest in building open-source IoT technology and devices, too big barrier of entry2. Lack of incentive in building an open source device, as open source projects will integrate with proprietary devices3. Smaller companies, communities cannot afford to sort plastics, leaves plastic that could be sorted but isn't4. Many smaller companies/communities do not have any space to put these devices5. People who are interested in the space need to use unfinished solutions, or need to use proprietary, expensive solutions6. Developers need to have a deep understanding of spectrometry to use the information available, to build a classification system

4. Scope

This project will...

Create an IOT platform, which:

- Should include...
 - A Frontend for the user to interact and control their IOT devices with
 - A Backend, with which the frontend will communicate. This will have an API for the IOT modules to communicate and register themselves with
 - An interface for saving data from modules in a user defined database
 - Documentation on how to set up the platform, how to create user defined modules and how to interact with the API endpoints
 - The code hosted on a Public Git Repository
 - Simple example modules, that display how to create IOT devices
 - Refined documentation that has been adjusted based on hobby user feedback
 - Be relatively cheap to reproduce for yourself
- Should not include...
 - A general IOT platform, that connects with devices made for other systems
 - A “ready out of the box” experience, instead it is meant for tinkerers and people who want to build their own modules

Build a module for the IOT platform that:

- Should include...
 - A way of determining and distinguishing between different plastics, these could include color or material
 - The code hosted on a Public Git Repository
 - Documentation on how this module was made, which can be used as reference by other developers
 - Documentation on how to build this module yourself
- Should not include...
 - A high-performance system, useable for industrial purposes
 - A library for general plastic analysis
 - A product for sale

5. Requirements

These are ranked by Priority

The IOT System

Functional Requirements:

1. **Shall** have a backend that manages connected modules
2. **Shall** have a way to connect to new modules on the network
3. **Shall** have an API with which connected modules can communicate with
4. **Shall** have a frontend, with which the user can interact, and control connected modules with
5. **Shall** have an interface with which to communicate with a user-defined database
6. **Should** have example modules written for it, showing basic functions of the system
7. **Should** notify users of errors or crashes throughout the system, on the frontend so the user can easily fix any issues
8. **Should** include a language library which programmers can use to easily create modules for the system

Non-Functional Requirements

1. **Shall** be an open-source project
2. **Shall** have documentation that contains information on how to set up the IOT hub
3. **Shall** have documentation that describes the process of writing a custom IOT module
4. **Shall** be able to run on a Raspberry Pi Model 4b, with multiple IOT devices connected at once
5. **Shall** be able to be installed on a machine comparable to the Raspberry Pi Model 4b, running Linux
6. **Shall** use end-to-end encryption to protect user information
7. **Shall** be easy to set up, and write modules for, by an experienced software developer
8. **Shall** run for extended periods of time without crashing, should be able to recover from some errors
9. **Should** be cheap for an end-user to reproduce for themselves
10. **Should** be able to be easily installed in a docker container

Plastic Sorting System

Functional Requirements

1. **Shall** be written as a module to the IOT system
2. **Shall** be able to distinguish between different plastics, using some sort of camera or sensor
3. **Shall** keep track of internal statistics, such as amount of each plastic sorted
4. **Shall** have a way of selecting the plastic to be tracked, through the IOT frontend
5. **Shall** save data to the database provided to the IOT system

Non-Functional Requirements

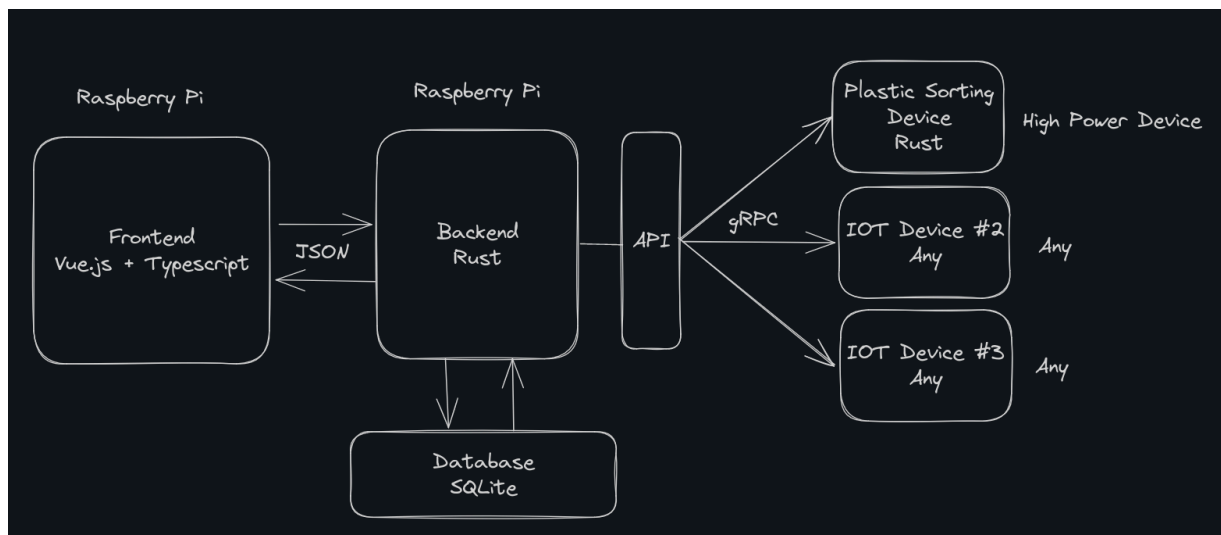
1. **Shall** have its code published on a public Git repository
2. **Shall** have extensive documentation, on how the user can build it for themselves, including a recommended parts list

3. **Shall** have documentation on how it was made, so it can be used as an example module by IOT platform developers

6. Methodology

As the main aim of this project is to build reliable, performant and scalable systems, choosing the right technology and development methodology is of particular importance. In **Figure 1**, a diagram of the architecture of the IOT System has been laid out. To complete this project each part of this diagram will need to be completed. This section will discuss some parts of this diagram, the technology that has been chosen to support them and the plan for completing them. It will also go over how the success of the totality of the project, but also individual parts, will be evaluated.

Figure 1:



Development Process

To ensure that this project is completed in an efficient and orderly way, agile development has been chosen. Agile fits this project well, as it is composed of multiple parts, which could fit into a sprint. Additionally, if during the development of the product requirements change, such as time constraints, agile development allows for faster requirement re-evaluation.

Figure 2: (image: Freepik.com)



Backend & IoT Devices

The main programming language for this project will be Rust, a safe, low-level and fast language. Rust has become popular in recent years due to its ability to be memory-safe (unless explicitly requested), without the overhead of garbage collection. This is quite important, due to the performance constraints introduced by IoT systems and these systems often being run for indefinite periods of time. The main competitor to Rust for this project would be C++, which certainly has its upsides. It is a mature language, with many resources and easy low-level memory access. However, due to Rust's memory-safety features and personal familiarity with the language it has been chosen for the backend for both the IOT and plastic distinguishing system.

Networking and Communication

To allow for easy communication between IoT modules and the backend-api *Remote Procedure Calls* (RPC) has been chosen, specifically gRPC. RPC allows for efficient and uncomplicated communication between internet devices, while abstracting away concepts such as sockets and data-interchange formats. GRPC is a popular, open-source, high performance RPC framework, with support for many languages.

Developing an Open Source application

To meet the requirement of *"shall be an open-source project"*, a number of established open-source conventions will be used. Two strong examples of such are the MIT and Apache licenses. The MIT license gives permission to use the provided code without restriction, allowing another developer to resell it or use it however they please [6]. In contrast, the apache license is more closed off, forcing derivative or 'recipients of this work' to also use the apache license, making that work also open-source [7]. In addition to choosing an open-source license, another important step is publishing the code in a public repository. For this a Github repository has been chosen, as it is one of the most popular and easy to use choices, while being free.

Testing

Non-functional requirements testing will be done in a multitude of ways. *"Shall be able to run on a Raspberry Pi Model 4b with multiple IOT devices connected at once."* This will be tested with performance testing. An example of such a test will include connecting many simulated clients, to test how many clients my backend could theoretically handle while running on the specified Raspberry Pi model. Another could include testing how many frontend clients sending requests could be handled at once. While this is not necessarily a good test for simulating a real life scenario, as normally the client will not have many frontend clients connected, it is a good measure of what is theoretically possible. Another performance test will include a mixture of both the mentioned tests, where some amount of frontend clients interact with the backend, while many IOT devices are also connected.

Another important aspect of the product is the user experience. To test if: *"shall be easy to set up, and write modules for, by an experienced software developer"* is fulfilled, a number of

peers will need to be used to collect feedback. One could test this through asking them to read through the documentation and testing them on their understanding. Another could be having a number of them try to set up the system themselves.

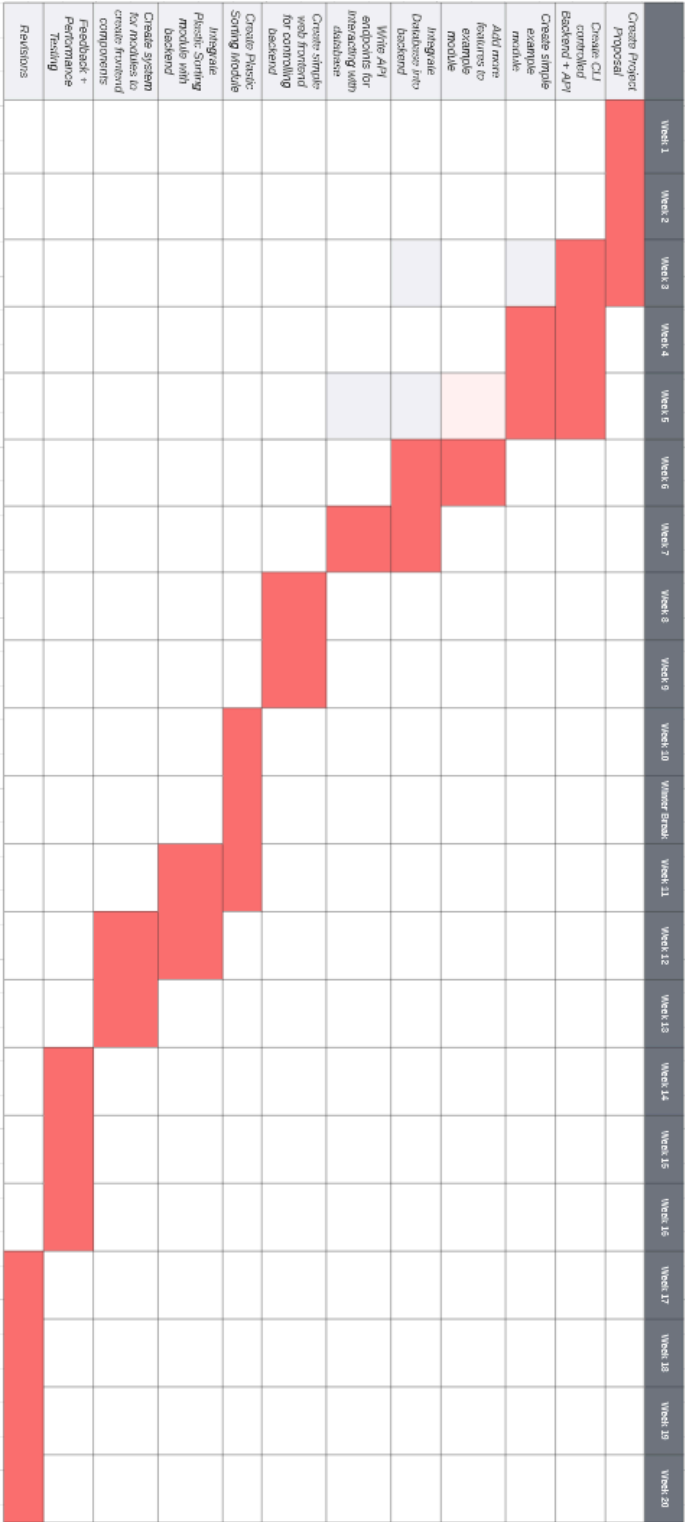
Functional testing will be done by evaluating if each functional requirement has been met. This will be done through asking peers to use the software and answer a questionnaire about the features that were available.

7. Timeline

To achieve the goals of this project, a well regimented work schedule will need to be followed. To create this schedule, each part of **Figure 1** has been split into appropriate steps. To view all these steps, see the Gantt chart in **Figure 2**. Below some steps of particular importance are highlighted. *Note that steps do not need to be a finalized state at the end of their allotted time, as there may need to be changes to their design as the project progresses*

- **Create CLI controlled Backend + API:** this contains creating the server, which allows IoT modules to connect to it. This server will run from a linux command line on the Raspberry Pi. It will also contain preliminary Api endpoints for requests from future IoT modules, however these will likely be changed in the future.
- **Create a simple example IoT module:** this module should be used to test and demonstrate the capabilities of the server and help to understand how API endpoints need to be changed. It will also help to get familiarized with the equipment.
- **Create a simple web frontend for controlling backend:** this part of the project will contain the process of making the example modules controllable through a simple GUI hosted on the web.
- **Create the Plastic Classification Module:** using what has been learned from the example modules, a plastic classification module will be created. This will take a significant amount of time and research, so it has been allocated over the winter break and given three extra weeks of time.
- **Create a system for modules to create frontend components:** an important part of the web frontend is flexibility. To enable that every IoT module will work with the platform a way for modules to specify their own web components needs to be created. The example modules will then be switched to this more dynamic method, instead of being hardcoded into the frontend.
- **Feedback + Performance Testing:** during the feedback stage, usability feedback on both the final product, but also the documentation will be collected. Additionally performance testing will be done
- **Revisions:** using feedback collected during the previous section, changes to the product and documentation will be made during this time.

Figure 3 Gantt chart:



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B Code Snippets

B.0.1 Code used for Experiments in Subsection 5.1.1

```
1 use std::error::Error;
2
3 use NOSHP_Client::{
4     client::{ClientState, NoshpClient,
5         Request, UserDefinedState},
6     client_config::{ClientConfig, ParsedConfig},
7 };
8
9 #[derive(Default)]
10 struct ExampleState {
11     text: String,
12 }
13 impl UserDefinedState for ExampleState {}
14
15 const CONFIG_PATH: &str = "./example_config.toml";
16 #[tokio::main]
17 async fn main() -> Result<(), Box<dyn Error>> {
18     let config = ClientConfig::load_config(CONFIG_PATH);
19     let config = match config {
20         Ok(r) => r,
21         Err(e) => {
22             eprintln!(
23                 "Error loading config: {}", e.to_string()
24             );
25             println!("Loading default config...");
26             ParsedConfig::default()
27         }
28     };
29
30     let client_handler = NoshpClient::new();
31     client_handler
32         .set_state(ExampleState {
33             text: String::from("hello world"),
34         })
35         .add_callback("Turn On", Box::new(turn_on_led))
36         .add_callback("Turn Off", Box::new(turn_off_led))
37         .run(config)
38         .await
39         .unwrap();
```

```
40
41     return Ok(());
42 }
43
44 fn turn_on_led(
45     _state: &mut ClientState<ExampleState>,
46     _req: Request
47 ) {
48     println!("Turn On")
49 }
50
51 fn turn_off_led(
52     _state: &mut ClientState<ExampleState>,
53     _req: Request
54 ) {
55     println!("Turn Off")
56 }
```

B.0.2 OS Error encountered during client spawning

Error when attempting to spawn 1000 clients.

Figure B.1: Linux TCP Error

```
Received Certificate
Successfully established Connection
thread 'tokio-runtime-worker' panicked at src/main.rs:49:18:
called 'Result::unwrap()' on an 'Err' value: transport error

Caused by:
  0: error trying to connect: tcp open error: Too many open files (os error 24)
  1: tcp open error: Too many open files (os error 24)
  2: Too many open files (os error 24)
```


B.0.3 Frontend API RegistrationService Definition

```
1 syntax = "proto3";
2 package frontend.registration;
3 import "frontendTypes.proto";
4
5 service FrontendRegistrationService {
6     rpc Register(RegistrationRequest)
7         returns (RegistrationResponse);
8     rpc GetConnectedDevices(ConnectedDevicesRequest)
9         returns (ConnectedDevicesResponse);
10 };
11
12 message RegistrationRequest {
13     string device_name = 1;
14 }
15
16 message RegistrationResponse {
17     string client_id = 2;
18 }
19
20 message ConnectedDevicesRequest {
21     string client_id = 1;
22 }
23
24 message ConnectedDevicesResponse {
25     repeated Device devices = 1;
26 }
27
28 message Device {
29     string device_name = 1;
30     string device_uuid = 2;
31     repeated frontend.types.DeviceCapabilityStatus
32         capabilities = 3;
33 }
```

B.0.4 Making API calls to the JSON Proxy

```
1 import { API_REGISTRATION_ADDRESS } from "@api_call_links";
2 import { Result, errAsync, okAsync } from "neverthrow";
3 import { frontend } from "@generated/generated";
4
5 export async function registerSelf(deviceName: string)
6 : Promise<
7   Result<frontend.registration.RegistrationResponse, Error>
8 > {
9   const req =
10     new frontend.registration.RegistrationRequest({
11       device_name: deviceName,
12     });
13
14   const res = await fetch(API_REGISTRATION_ADDRESS, {
15     method: "POST",
16     body: JSON.stringify(req),
17     headers: {
18       "Content-type":
19         "application/json; charset=UTF-8",
20     },
21   });
22
23   try {
24     const parsed:
25       frontend.registration.RegistrationResponse =
26       await JSON.parse(await res.text());
27     return okAsync(parsed);
28   } catch (e) {
29     return errAsync(new Error("Malformed Api Response"));
30   }
31 }
```

C Programming Topics

C.1 Rust Terminology Explained

This section contains a simple list of Rust terms and their meaning in relation to traditional programming terms.

- **Crate:** Rust's version of a library. Due to the way generics are handled at compile-time in Rust, Rust libraries are usually shipped as their source code, therefore they are not technically libraries in the traditional sense of the word. This also means that most Rust crates are open-source and need to be compiled at least once. This is part of the reason that Rust projects, especially ones with a lot of crates, take a long time to compile.
- **Trait:** The equivalent of an interface in Rust. If a struct wants to implement a certain trait, they will need to implement all functions defined in that trait. This allows for powerful behavior with generics.

C.2 Libraries used for this project

Below is a list of major libraries used during the creation of this project:

Rust

- **Tokio:** An asynchronous runtime commonly used in Rust projects, required for some dependencies (such as the gRPC and HTTP servers) to function. Enables use of Async/Await syntax.
- **Tonic:** gRPC and Protobuffer support in Rust, including transpiling protobuffers to Rust code and running a gRPC server.
- **RSA:** An RSA library for Rust, used to generate private/public key pairs, sign messages and encrypt/decrypt messages
- **Serde:** Serialization and deserialization of datastructures in Rust. In combination with `serde-json` allows easy serialization and deserialization of JSON data.
- **RPPal:** Easily interface with Raspberry Pi GPIO pins.
- **Actix-web:** HTTP web server implementation in Rust.
- **Clap:** Command line argument parser for Rust

Javascript

- **VueJS:** A web development framework that allows for easy frontend development
- **Typescript:** Types in Javascript, all typescript code is transpiled to native Javascript
- **ProtobufJs:** A protobuf implementation that allows transpilation of protobuffers to Typescript