Chair for Embedded Systems
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Master's Thesis

Implementation of an IoT based Electronic Voting Machine

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Contents

Abstract

Eine kurze Zusammenfassung der Ausarbeitung.

List of Abbreviations

BSI Bundesamt für Sicherheit in der Informationstechnik

E2E End-to-end

VVSG Voluntary Voting System Guidelines

ZK Zero-Knowledge

PKE Public-Key Encryption

BLE Bluetooth Low Energy

AES Advanced Encryption Standard

SHA Secure Hash Algorithm

RSA Rivest-Shamir-Adleman

RNG Random Number Generator

TRNG True Random Number Generator

PRNG Pseudo Random Number Generator

HMAC Keyed-Hash Message Authentication Code

KDF Key Derivation Function

ECC Elliptic Curve Cryptography

1. Introduction

In the introduction the author motivates the work and explains the relevance of the work.

1.1. Ziele dieser Arbeit

Die Ziele der Arbeit werden hier erläutert.

1.2. Überblick

Der Autor führt einen potentiellen Leser durch die Arbeit und beschreibt kurz, was den Leser in den folgenden Kapiteln erwartet.

2. Background

2.1. Cryptography

Cryptography is the science of securing information through encryption. Encryption, also referred to as ciphering, involves transforming a message into an incomprehensible format [Ert07, p. 18]. The security of all cryptographic methods fundamentally relies on the difficulty of guessing a secret key or obtaining it through unauthorized means. While it is possible to guess a key, the likelihood diminishes as the lenght of the key increases. It should be noted that there is no absolute security in cryptography [Ert07, p. 25].

Practically all cryptographic methods aim to achieve one or more of the following properties [Ert07, p. 18]:

- **Confidentiality:** The aim of confidentiality is to make it impossible or difficult for unathorized persons to read a message [Ert07, p. 18].
- **Authenticity:** This property ensures that the recipient can verify the identity of the sender, ensuring that the message is not from an unauthorized sender [Ert07, p. 18].
- **Integrity:** This denotes that the message has not been altered during transmission [Ert07, p. 18].
- **Non-repudiation:** This means that the sender cannot later deny having sent a message [Ert07, p. 18].

Cryptographic algorithms are mathematical functions used for encryption and decryption [Ert07, p. 19]. A given cryptographic algorithm can be applied in various ways across different applications. To ensure that an application operates consistently and correctly, cryptographic protocols are defined. Cryptographic protocols are procedures that govern the flow of transactions within specific applications [Ert07, p. 22].

2.2. Cryptography in Voting Systems

The integration of cryptographic methods into voting systems has been a topic of discussion for several decades [Mos+24, p. 6]. In 1981, David Chaum introduced a cryptographic technique based on public key cryptography that effectively conceals both the identity of participants and the content of their communication. The untracable mail system requires messages to pass through a cascade of mixes (also known as a decryption mix nets) [Cha81, p. 86] [Mos+24, p. 84]. Chaum proposes that these cryptographic techniques can be adapted for use in elections. In this model, individual voters communicate with a record-keeping organization or an authorized party under a unique pseudonym, provided that this pseudonym appears in a roster of approved clients. This allows the organisation to verify that the message was sent by a registered voter while ensuring that the message was not altered during transmission [Cha81, p. 84].

The application of Chaum's method adheres to the four fundamental properties of cryptographic security:

- **Confidentiality:** Ensures that the voter's communication remains private from unauthorized entities.
- **Authenticity:** Confirms that the message indeed originated from a registered voter.
- **Integrity:** Guarantees that the message content was not modified during transmission.
- **Non-repudiation:** Provides assurance that the sender cannot deny having sent the message.

2.3. Building Public Trust in Electronic Elections

For a voting process to be deemed trustworthy, it is essential to provide voters and observers with compelling evidence that the election has been conducted properly while maintaining confidentiality (e.g., ballot secrecy). This aspect of public trust is further complicated by the necessity of trusting not only election officials but also the software and hardware utilized in the election process. Fortunately, modern cryptographic techniques provide viable solutions for ensuring both verifiability and confidentiality [Mos+24, p. 6].The objective of employing such methods is to minimize reliance on individual components of the voting system. Independent auditors

should be able to verify the correctness of the final election results without compromising the confidentiality of individual votes. Essentially, the goal is to reveal no more information about the votes than what can be inferred from the final tally [Mos+24, pp. 6, 10].

2.4. End-to-End Verifiability

A study conducted by the German Federal Office for Information Security Bundesamt für Sicherheit in der Informationstechnik (BSI) highlighted that **end-to-end End-to-end (E2E) verifiability** is regarded as the gold standard for achieving the aforementioned goal in electronic voting systems [Mos+24, p. 10]. Furthermore, the Voluntary Voting System Guidelines Voluntary Voting System Guidelines (VVSG) 2.0, adopted by the U.S. Election Assistance Commission, mandates that voting systems must be software-independent. These guidelines are designed for designers and manufacturers developing voting systems [Com17]. The VVSG 2.0 outlines two primary methods for achieving software independence - the use of independent voter-verifiable paper records and E2E verifiable voting systems [Com21b, p. 181].

2.4.1. Key Components of End-to-End Verifiability

E2E verifiability encompasses two principal components [Ben+14, p. 2]:

- **Cast As Intended:** Voters can verify that their selections - whether indicated electronically, on paper, or by other means - are recorded correctly [Ben+14, p. 2].

- **Tallied As Cast:** Any member of the public is able to verify that every recorded vote is included correctly in the final tally [Ben+14, p. 2].

All E2E Verifiable voting systems incorporate cryptographic building blocks at their core. The most important and recurring cryptographic building blocks include [Mos+24, p. 13]:

- **Public-Key Encryption Public-Key Encryption (PKE):** Most verifiable voting systems use PKE to encrypt sensitive data, such as votes, using a public key.This ensures that authorized parties possessing the corresponding secret key can decrypt the data [Mos+24, p. 13].

- **Commitments:** Similar to PKE, commitments also serve to protect sensitive

data. However, in this case, the data cannot be decrypted using a secret key, but only with specific information generated during the individual commitment process, which is then distributed to selected parties [Mos+24, p. 13].

- **Digital Signatures:** These are commonly used in voting systems to allow different parties to confirm that the messages they are receiving originate from the indicated party [Mos+24, p. 13].

- **Zero-Knowledge Zero-Knowledge (ZK) Proofs:** This technique permits a party to demonstrate that it has correctly performed a certain computational operation without revealing any additional information, such as the secret key involved in the computation [Mos+24, p. 13].

- **Threshold Secret Sharing:** This method is utilized to distribute information about a secret (e.g., a secret key) among multiple parties. A predetermined threshold of those parties must cooperate to reconstruct the secret from their individual shares [Mos+24, p. 13].

2.5. End-to-End Verifiable Software Libraries

Implementing an E2E verifiable voting system is a multifaceted challenge that requires specialized knowledge in cryptography alongside a foundation in software engineering. Successful implementation requires a comprehensive understanding of the specific algorithms and their correct implementation. Fortunately, several high-quality, well-maintained and tested software libraries are available, designed to simplify the implementability of E2E verifiable voting systems through robust cryptographic building blocks. Notable libraries include **CHVote**, **ElectionGuard**, **Verificatum**, **Belenios**, and **Swiss Post** [Mos+24, pp. 11, 26]. All of the aforementioned libraries use ElGamal's malleable PKE scheme, which is the most prevalent implementation in today's systems. The original ElGamal scheme is multiplicaticely homomorphic, frequently an exponential variant of ElGamal is employed, making it additively homomorphic [Mos+24, p. 40].

2.6. ElectionGuard Overview

Microsoft's **ElectionGuard** is a toolkit designed to provide E2E verifiable elections by seperating cryptographic functions from the core mechanisms and user interfaces of voting systems. This seperation empowers ElectionGuard to offer simple inter-

faces that can be used without requiring cryptographic expertise. Consequently, existing voting systems can function alongside ElectionGuard without necessitating their replacement, while still producing independently-verifiable tallies [Ben+24, pp. 1–2].

The cryptographic design of ElectionGuard is largely inspired by the cryptographic voting protocol developed by Cohen (now Benaloh) and Fischer in 1985, as well as the voting protocol by Cramer, Gennaro, and Schoenmakers in 1997 [Ben+24, p. 5]. One of the first pilots employing ElectionGuard was conducted in Preston, Idaho, on November 8, 2022, using the Verity scanner from Hart InterCivic, integrated with ElectionGuard. This pilot provided one of the first opportunities to see how an E2E verifiable election operates within a real election context. [23a, p. 4].

In all applications, the election process utilizing ElectionGuard begins with a key-generation ceremony, during which an election administrator collaborates with guardians to create an election key. The administrator will then work again with the guardians to produce verifiable tallies at the conclusion of the election. What transpires in between these stages can differ [Ben+24, p. 20]. The flexibility of ElectionGuard is a novel feature and one of its primary benefits [Ben+24, p. 22].

2.7. Phases of ElectionGuard

The election process in ElectionGuard can be divided into three main phases: Pre-election, Intra-election, and Post-election. Each phases involves distinc activities. Below, we will explore each phase in detail.

2.7.1. Pre-election

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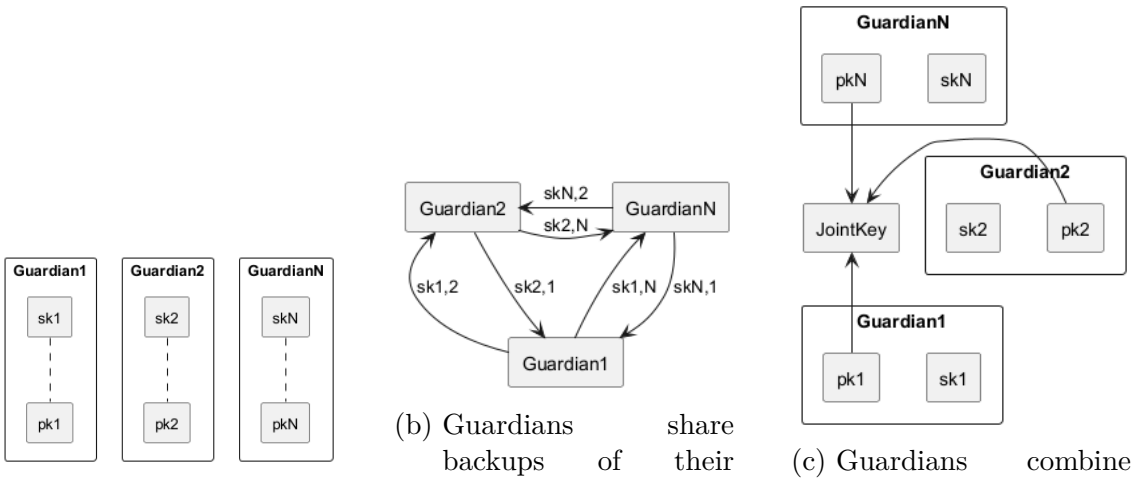
The pre-election phase encompasses the administrative tasks necessary to configure the election and includes the key generation ceremony.

The **election manifest** defines the parameters and structure of the election. It ensures that the ElectionGuard software can correctly record ballots. The manifest defines common elements when conducting an election, such as locations, candidates, parties, contests, and ballot styles. Its structure is largely based on the NIST SP-1500-100 Election Results Common Data Format Specification and the Civics Common Standard Data Specification [].



(a) Each guardian generates a key pair

(b) Guardians share backups of their private keys with each other

(c) Guardians combine their public keys to create a joint key

Figure 2.1.: Key Ceremony. Adapted from []

In addition to defining the election, specific **cryptographic parameters** must be defined. A significant aspect is selecting mathematical constants used in cryptographic operations. The ElectionGuard specification provides both standard and reduced values for these constants [BN22, pp. 21, 36–38]. Furthermore, the pre-election phase defines the number of participating guardians and the minimum quorum of guardians required for the post-election phase. These parameters play a significant role in the key generation ceremony [Ben+24, pp. 8–9].

The key generation ceremony involves trustworthy individuals, known as **guardians**, who collaborate to create a joint election key through the multiplication of individual public keys. This joint key is essential for encrypting data, as it requires all guardians to apply their private keys for decryption. This process minimize the risk associated with a single party being responsible for the property of ballot confidentiality. If some guardians are unavailable in the post-election phase the quorum count allows a specified number of guardians to reconstruct missing private keys by sharing "backup" copies among themselves during the pre-election phase [Ben+24, p. 8] []. It is crucial to recognize that at least some level of trust is necessary for any component of the system. To ensure the distribution of trust is effective, it is essential that the guardians are genuinely independent of each other [Mos+24, p. 92].

The last step in the pre-election phase involves loading the election manifest, cryptographic parameters, and the joint key into an encryption device responsible for encrypting ballots throughout the intra-election phase. [Ben+24, p. 8].

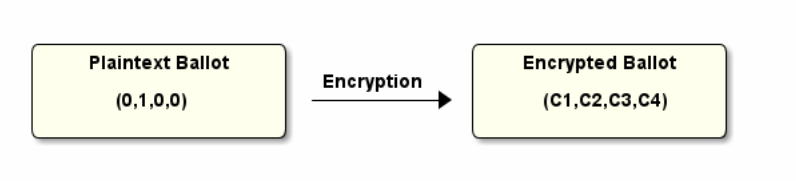


Figure 2.2.: Representation of plain and encrypted ballots

2.7.2. Intra-election

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During the election phase, the ballots are encrypted and consist entirely of exponential ElGamal encryptions of binary values: a "1" signifies support for a particular option, while a "0" indicates a lack of support [Ben+24, p. 11] [BN22, p. 12]. In scenarios where a voter has multiple options, such as four choices in a single contest, the encrypted ballot will contain four corresponding encrypted bits. The exponential form of ElGamal encryption possesses an additive homomorphic property; therefore, the product of the encrypted reflects the count of selected options [BN22, p. 5].

A simple representation of this scenario is shown in Figure 2.2. The plaintext ballot consists of four options in which the second option has been selected. When all encrypted values are combined homomorphically by multiplying them, the result encrypts the count of selections made. This technique ensures that the ballot does not contain excessive votes [BN22, p. 5].

While encryption itself is a straightforward process, a significant portion of ElectionGuard's effort is dedicated to creating externally verifiable artifacts to confirm that each encryption is well-formed [BN22, p. 3]. ZK proofs are employed to validate that the encryptions correspond to the values of 1 and 0 [Ben+24, p. 11]. A Chaum-Pedersen proof verifies whether an encryption repreents a specific value. By utilizing the Cramer-Damgård-Schoenmakers technique, it can be demonstrated that an encryption belongs to a specific set of values, such as 0 or 1. The proofs are made non-interactive through the Fiat-Shamir heuristic [BN22, pp. 6, 13].

Once the encryption of a ballot is finalized, a confirmation code is generated for the voter [BN22, p. 17]. This confirmation code is a cryptographic hash derived entirely from the encrypted ballot [Ben+24, p. 14]. With the confirmation code, a voter can either cast the associated ballot or choose to spoilt it and restart the ballot preperation process. The two choices are mutually exclusive, since challenging reveals the selections on the ballot. A challenged ballot can never be cast, while a cast ballot cannot be challenged anymore. This casting and spoiling mechanism acts as an interactive proof to assure voters that their selections have been correctly

encrypted [BN22, p. 17] [].

2.7.3. Post-election

At the end of the voting period, all encrypted ballots submitted for tallying are homomorphically combined to produce an encrypted tally [BN22, pp. 5, 18] [Ben+24, p. 15]. Each available guardian utilizes their private key to generate a decryption share, which represents a partial decryption for the encrypted tally or spoiled ballots. Decrypting spoiled ballots is unnecessary for determining the election outcome but may be performed to support cast-as-intended verifiability [Ben+24, pp. 15, 17] [BN22, p. 18]. To verify the correctness of these shares, guardians also publish a Chaum-Pedersen proof of each share [BN22, p. 18]. The full decryption is achieved through the ordinary multiplication of these partial decryptions. If any guardians are unavailable during decryption, the remaining guardians can utilize the backups to reconstruct the missing shares [].

To conclude the election, the final step involves the publication of the election record, which is vital for the integrity of a verifiable election. This record contains a complete account of all election artifacts, including the election manifest, cryptographic parameters, and the decrypted tally [BN22, p. 24]. Independent verification software can be leveraged at any time after completion of an election to confirm the election's integrity [Ben+24, p. 6]. The true value of a verifiable election is fully realized only when the election is actively verified by voters, election obsevers, or news organisations [BN22, p. 17].

2.8. ESP32-WROOM-32 Overview

The **ESP32-WROOM-32** is a powerful microcontroller module that integrates Wi-Fi, Bluetooth, and Bluetooth Low Energy Bluetooth Low Energy (BLE) technologies, along with 4MB of integrated SPI flash memory. At the core of this module is the **ESP32-D0WDQ6** chip, which belongs to the ESP32 series of chips [23b, p. 6]. In the context of this thesis, the term **ESP32** broadly refers to the family of chips within the series rather than a specific variant.

It's important to note that the ESP32-WROOM-32 module is marked as not recommended for new designs. Instead, designers are advised to use the ESP32-WROOM-32E, which is built around either the ESP32-D0WD-V3 or the ESP32-D0WDR2-V3 chips. These later revisions rectify some hardware issues present in previous versions [24b, p. 1], [25b, p. 11], [24a, pp. 3–4].The ESP32-D0WDQ6 chip is susceptible to

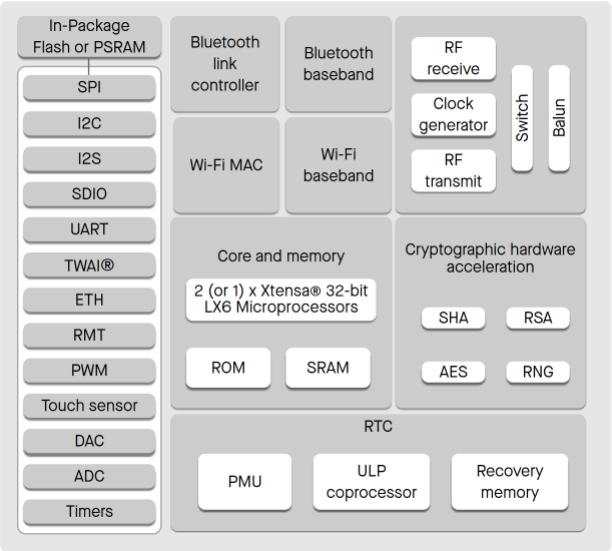


Figure 2.3.: ESP32 Functional Block Diagram

fault injection attacks. Sucessfully carrying out a fault injection attack could enable an attacker to recover the Flash Encryption key. This key allows unauthorized access to the device's flash contents, including firmware and data stored in flash. Such an attack necessitates physical access to the device [19].

ESP32 is designed for robustness, versatility, and reliability across a wide range of applications and power scenarios [25b, p. 2]. Due to its low power consumption, ESP32 is an ideal choice for IoT applications spanning smart homes, industrial automation, consumer electronics, healthcare, and battery-powered electronics [25b, p. 5] [23b, p. 6].

ESP32s come with either a single or dual-core Xtensa® 32-bit LX6 microprocessor, operating at frequencies of up to 240 MHz. They come equipped with:

- **448 KB of ROM** for booting and core functions [25b, pp. 4–5]
- **520 KB of SRAM** for data and instructions [25b, pp. 4–5]
- **34 programmable GPIOs** [25b, pp. 4–5]
- **Cryptographic hardware acceleration capabilities** [25b, pp. 4–5]

The supported cryptographic hardware acceleration capabilities include Advanced Encryption Standard (AES), SHA, RSA, and RNG [25b, pp. 4–5]. A functional block diagram illustrating the components and subsystems within ESP32 is presented in Figure 2.3.

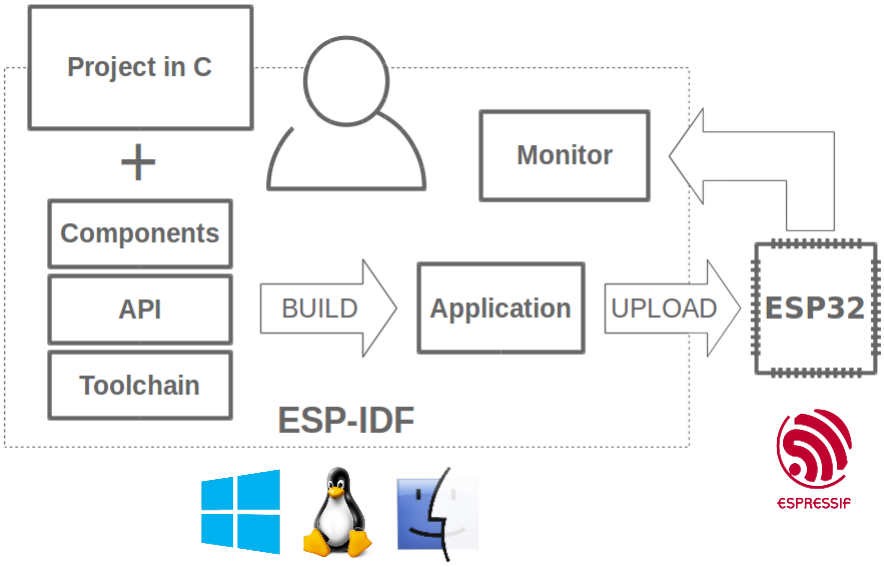


Figure 2.4.: ESP32 Functional Block Diagram

2.8.1. Development Environment

The freeRTOS operating system powers the ESP32 [23b, p. 6]. For application development, Espressif, the company behind the ESP32, offers the ESP-IDF (Espressif IoT Development Framework). ESP-IDF encompasses a comprehensive toolchain, API components, and defined workflows tailored for ESP32 application development **esp32-prog**. The development workflow for ESP-IDF is depicted in Figure **??**.

An ESP-IDF project can be seen as an amalgamation of numerous components coded in C. Components are modular pieces of standalone code that are compiled into static libraries which are subsequently linked into a project. These components can originate from various sources, including external git repositories or Espressif's Component Manager. Each component may also come with a Kconfig file, allowing users to configure the component through a text-based menu system [25a].

3. Implementation of an IoT based Electronic Voting Machine

3.1. Hardware Reference

Basic Component List	Number	Notes
NodeMCU ESP32	1	Development board for prototyping
1,8" LCD Display Module	1	128x160 Pixel, includes microSD Slot
Button module with 2 Buttons	1	For interacting
Jumper Wires Female to Male	22	For connecting components
Breadboard	1	For building circuits

Table 3.1.: Basic Component List for Guardian Prototype

As shown in Table 3.1, the hardware components used in our prototype include a ESP32 development board, an LCD display module, jumper wires, breadboard and a module with 2 Buttons. The connectivity of these components are shown in the schematic in Figure 3.1. The NodeMCU ESP32 development board is used as the Main Controller. The LCD display module is used to display information to the user. The button module is used to interact with the user. The jumper wires are used to connect the components. The breadboard is used to build the circuits.

3.1.1. NodeMCU ESP32 Development Board

The NodeMCU ESP32 development board is equipped with the ESP32-WROOM-32 module.

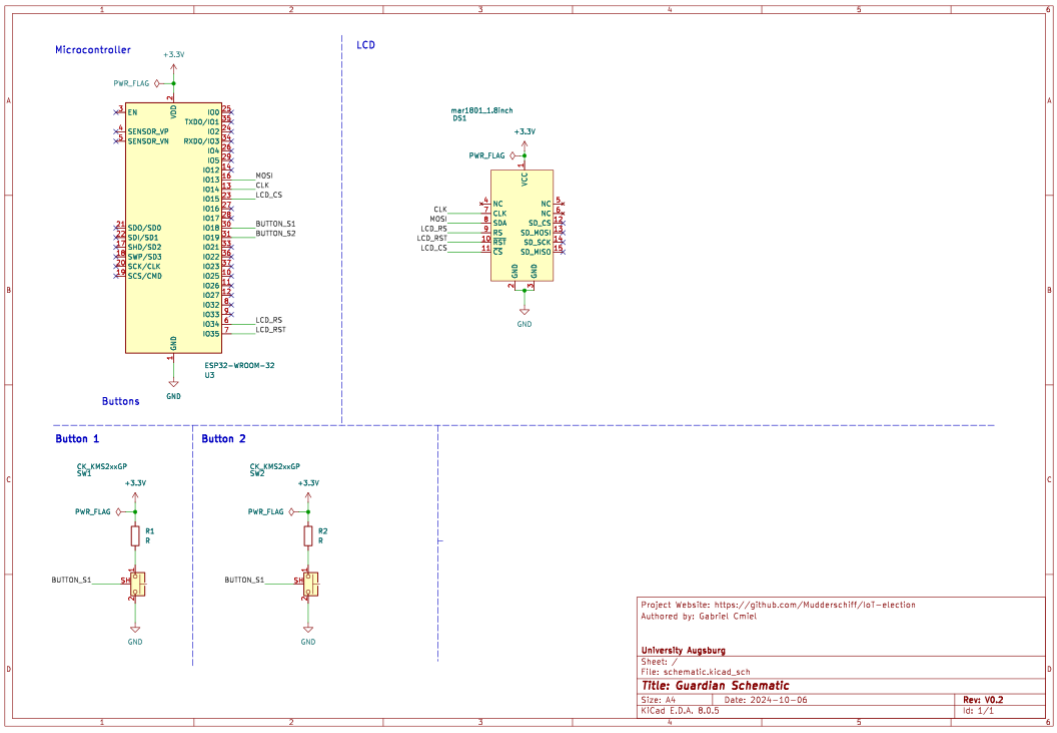


Figure 3.1.: Schematic of the Guardian Prototype

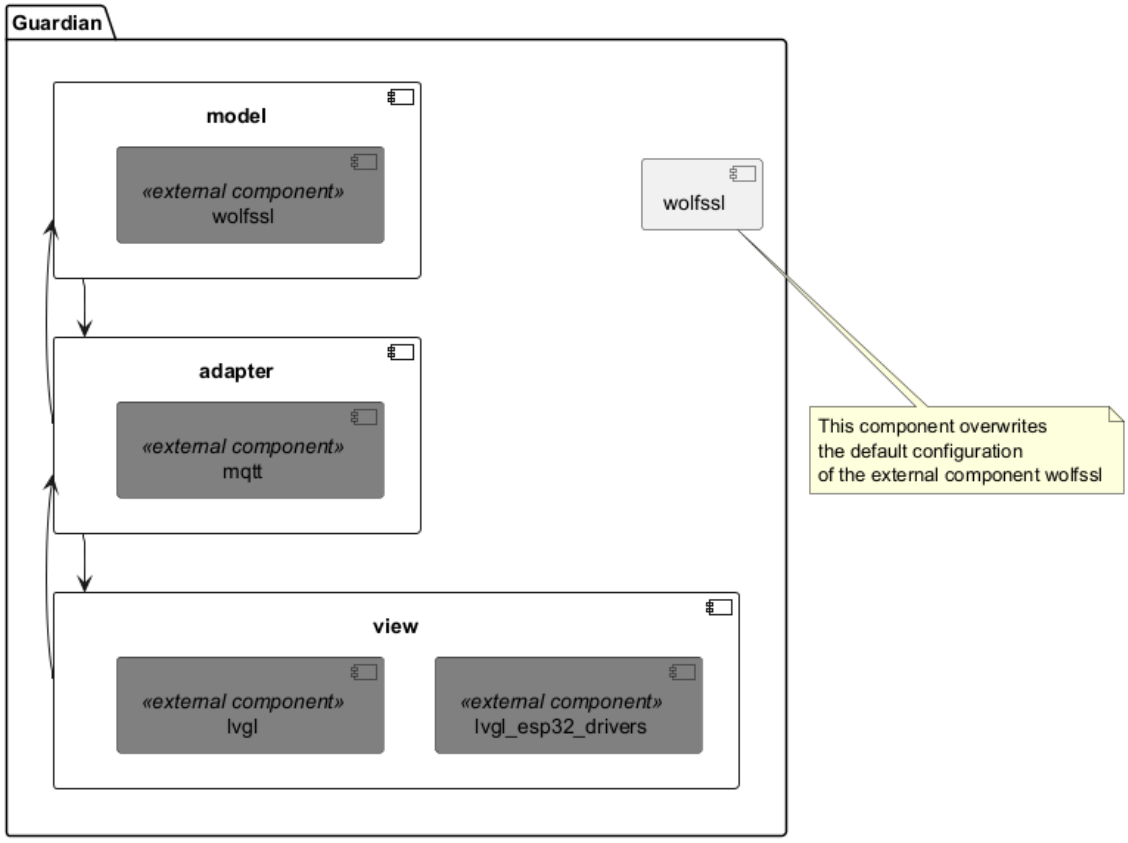

Guardian
model
«external component»
wolfssl
adapter
«external component»
mqtt
view
«external component»
lvgl
«external component»
lvgl_esp32_drivers
wolfssl
This component overwrites
the default configuration
of the external component wolfssl

Figure 3.2.

3.2. Computation

ElectionGuard uses integer ElGamal cryptography within its specific cryptographic operations. The system performs four key operations on very large integer values: **modular exponentiation**, **modular multiplication**, **modular addition**, and **SHA-256** hash computation. To handle the large integer values involved in these operations, specialized libraries for large integers may be employed, or the operations can be developed from scratch [BN22, pp. 21, 25–26]. When developing these modular operations from the ground up, it is common for intermediate values to become excessively large. Techniques such as modular reduction are often necessary to ensure that values remain manageable [BN22, pp. 21, 25–26].Consequently, employing optimized libraries for modular arithmetic becomes crucial for achieving good performance [Ben+24, p. 22].

3.2.1. Cryptographic constants

Among all computations in ElectionGuard, modular exponentiation presents the highest computational cost, serving as the primary limiting factor in performance analysis [BN22, p. 22]. Within ElectionGuard, most modular exponentiation operations utilize a fixed base, which may be either the generator (g) or a public key [Ben+24, p. 22]. The generator G is a mathematical constant specified in the ElectionGuard specification.

The standard baseline parameters include:

- A 4096-bit prime (p) [BN22, p. 22]
- A 4096-bit generator (g) [BN22, p. 23]
- A 256-bit prime (q) [BN22, p. 21]

Alternatively, the system can also utilize reduced baseline parameters, which consist of:

- A 3072-bit prime (p) [BN22, p. 36]
- A 3072-bit generator (g) [BN22, pp. 36–37]
- A 256-bit prime (q) [BN22, p. 36]

For this application, we opt for the reduced parameters, as they offer enhanced

performance, albeit at the expense of lower security [BN22, pp. 36–37]. The cryptographic constants used in the implementation can be found in Appendix A.2.1.

3.2.2. Comparison of ElectionGuard Implementations

The Python reference implementation of ElectionGuard utilizes the C-coded Gmpy2 library for large integer arithmetic. In contrast the C++ and Kotlin implementations rely on the HACL* C library for similar purposes []. Interestingly, both implementation use C-coded libraries for handling large integer arithmetic. Moreover, the C++ implementation incorporates pre-computed tables to speed up certain modular exponentiations []. This optimization is possible because many of the exponentiations are performed with a fixed base, either the constant generator (g) or a public key. The pre-computed tables contain specific powers of these bases [].

Feasability of the Python reference on ESP32

The Python reference implementation encompasses the entire ElectionGuard specification [Ini]. Running the Python reference implementation on the ESP32 may be achievable through **MicroPython**, an implementation of Python 3.x targeted for microcontrollers and embedded systems. MicroPython mirrors and adapts the functionalities of the standard Python library to accommodate the limitations inherent to to microcontrollers, such as restricted memory and processing speed [Mic] [IE20, p. 234]. There are drawbacks to this approach, as certain essential modules, functions, and classes may be absent in MicroPython [Mic]. Additionally, applications developed in MicroPython are prone to memory fragmentation and may experience issues with objective expending in size. [IE20, p. 234]. Depending on the complexity of the task and memory allocation, the performance of MicroPython might be inferior to that of a C implementation [IE20, p. 237]. For instance, in a comparative study of software-based SHA-256 computation for the ESP32, the C implementation outperformed the MicroPython implementation by 45% [IE20, p. 237].

Feasability of the C++ reference on ESP32

The ElectionGuard C++ reference implements only a subset of the ElectionGuard specification, focusing on the encryption library and thus addressing only intra-election functionalities citecpp-reference. ESP-IDF supports the development of applications in C++. Certain C++ features, such as exception handling, must be enabled in the project configuration. This results in a slight increase in the

application binary size [25a]. The Runtime Type Information (RTTI) feature can remain disabled since dynamic cast conversions and the typeid operator are not utilized in the ElectionGuard C++ implementation. C++ Threads are supported, these are implemented as wrappers around C pthreads, which in turn wrap around FreeRTOS tasks [25a].

Upon porting the C++ implementation to an ESP32 component, we conducted tests using the provided C Unit Tests, particularly focusing on the ElGamal encryption test. However, the test failed upon invoking the **pow_mod_p()** function, which is intended to optimize modular exponentiation by utilizing pre-computed tables.

Listing 3.1: FixedBaseTable Definition

```
typedef std::array<std::array<uint64_t[MAX_P_LEN], OrderBits>,
    TableLength> FixedBaseTable;
```

The **FixedBaseTable** is defined as a 2D array. Here, **MAX_P_LEN** denotes the lenght of each **uint64_t** array, **OrderBits** indicates the number of **uint64_t** arrays in each inner array, and **TableLength** represents the number of inner arrays in the outer array.

The **pow_mod_p()** function is optimized for specific parameters: (order_bits = 256), (window_size = 8), and (table_length = 32). Any modifications to these parameters could affect the function's internal operations. The window_size determines into how many groups of (k) bits the exponent is parsed, while the order_bits reflect the number of possible values within each group. With an 8-bit window_size, the order_bits would amount to 256 $(2^8)[BN22, P.22]$.

To estimate the memory requirements of the **FixedBaseTable**, we can calculate the total size in bytes as follows:

$$\text{FixedBaseTableSize} = \text{sizeof(uint64\_t)} \times \text{MAX\_P\_LEN} \times \text{OrderBits} \times \text{TableLength} \tag{3.1}$$

Given that **MAX_P_LEN** is defined as 64, substituting into the equation yields a total size of 4MB:

$$\text{FixedBaseTableSize} = 8 \times 64 \times 256 \times 32 = 4194304\text{bytes} = 4\text{MB} \tag{3.2}$$

If we calculate the size of the **FixedBaseTable** with our reduced baseline parameters, we find:

$$\text{FixedBaseTableSize} = 8 \times 48 \times 256 \times 32 = 3145728\text{bytes} = 3\text{MB} \tag{3.3}$$

The ESP32 features (320 KB) of DRAM. Due to a technical limitation, a maximum of (160 KB) is available for dynamic allocation [25c]. Consequently, the **FixedBaseTable** exceeds the memory capacity of the ESP32. While reducing the **window_size** results in smaller tables and reduced memory usage, it simultaneously increases the number of multiplications [BN22, p. 22]. Considering these resource limitations and the fact that the ElectionGuard C++ implementation is designed with Intel Atom-level processor performance in mind, alongside the memory requirements of the **FixedBaseTable** optimization, it becomes evident that the C++ implementation is not feasible on the ESP32 [].

3.2.3. Implementation Strategy for ESP32

As previously discussed, both the Python and C++ reference implementations prove impractical for porting to the ESP32. While the Python implementation may be feasible with MicroPython, the performance may be suboptimal due to possible memory fragmentation. The C++ implementation, on the other hand, is not viable due to memory and processor constraints. Ultimatelty, a pure C implementation stands out as the most feasible approach for the ESP32. To achieve optimal performance on the ESP32, we must consider the dedicated hardware accelerators available. The ESP32 supports several cryptographic hardware acceleration capabilities including AES, SHA, RSA, and RNG as illustrated in the functional block diagram 2.3. These hardware accelerators significantly enhance operational speed and reduce software complexity for the aforementioned cryptographic primitives [25b, p. 32].

In ESP32 the cryptographic primitives are implemented in a fork of the mbedTLS library. The fork includes patches related to hardware routines for on-board cryptographic hardware acceleration [25c]. Optionally, a port of the WolfSSL library is also available, which also includes ESP32-specific hardware routines [Inc25, p. 114]. To sucessfully run WolfSSL on the memory-restricted ESP32, it is essential to configure the component to use less memory, albeit at a potential performance cost. An excerpt from the Component configurations for WolfSSL can be found in Appendix A.1.1

3.2.4. RNG

In the context of ElectionGuard, generating random values is crucial for various operations, including the generation of private keys and the use of nonces in various

proofs [BN22, pp. 9, 13]. The ESP32 features a True Random Number Generator True Random Number Generator (TRNG) that can produce 32-bit random numbers that are suitable for cryptographic purposes. Unlike Deterministic Random Bit Generators **DRBG!** (**DRBG!**), which rely on algorithms to produce random numbers, the ESP32's TRNG generates randomness from physical processes. This includes leveraging thermal noise and asynchronous clock mismatches, ensuring a high level of unpredictability, essential for cryptographic operations [25c, p. 604].

To utilize the TRNG effectively, it is necessary to enable a source for thermal noise; otherwise, the TRNG will return pseudo-random number [25c, p. 609]. The High-speed ADC is enabled automatically when the Wi-Fi or Bluetooth module is enabled, which is the case in our design [25c, p. 610]. When the noise is sourced from the high-speed ADC, it is advisable to read the **RNG_DATA_REG** register at a maximum rate of 5 MHz [25c, p. 609]. However, the values from the high-speed ADC can be saturated in extreme cases, leading to lower entropy. It is advisable to enable the SAR_ADC as a secondary noise source. The **RNG_DATA_REG** register should then be read at a maximum rate of 500 kHz to obtain the maximum entropy [25c, p. 609].

In our ESP32 implementation, as outlined in Appendix A.2.2, we aim to generate random values below a specific mathematical constant (q), which is a 256-bit prime number. To achieve this objective, we fill a buffer with 256-bits of randomness utilizing the system API function esp_fill_random(). To ensure that the generated 256-bit number does not exceed (q), we perform a modulo operation with the value of (q). To obtain a 256-bit number, esp_fill_random() reads the 32-bit RNG_DATA_REG register eight times. The function will busy-wait if the reading frequency exceeds acceptable limits [25c].This limitation arises because the function must ensure that sufficient external entropy has been introduced into the hardware RNG state. For our use case the function should not delay. If the function delays, we should consider using a strong software **DRBG!** such as mbedTLS CTR-DRBG, mbedTLS HMAC-DRBG, or WolfSSL DRBG, which can be initialized with the TRNG values as a seed [25c] [Inc25, p. 588].

3.2.5. SHA Accelerator

ElectionGuard encrypts non-vote data, such as cryptographic shares of a guardian's private key, using hashed ElGamal encryption. This method employs a key derivation function Key Derivation Function (KDF) to generate a key stream that is XORed with the data. The Keyed-Hash Message Authentication Code Keyed-Hash Message Authentication Code (HMAC) is used for message authentication and is integral to the implementation of the KDF. In ElectionGuard, HMAC is instantiated as HMAC-SHA-256, which uses the SHA-256 function [BN22, p. 7]. An

implementation of the HMAC-SHA-256 function can be found in Appendix **??**.

The SHA-256 hash function is frequently applied in various cryptographic operations within ElectionGuard, with implementation details provided in Appendix A.2.3. The ESP32 microcontroller is equipeed with a SHA Accelerator that significantly enhances the performance ofSHA operations compared to purely software implementations [25c, p. 589]. Notably, this accelerator supports the SHA-256 algorithm used in ElectionGuard. However, it processes only one message block at a time and does not handle padding operations. Therefore, software must manage the division of longer messages into 512-bit blocks, along with any required padding [25b, p. 2].

In multi-core environments, libraries like mbedTLS and WolfSSL implement fallback mechanisms to software implementations when multiple concurrent hashing operations are initiated. As a result, simultaneous computations revert to software calculations [Espb] [Incb]. Benchmarks uzilizing mbedTLS at processor speeds of 240 MHz reveal that hardware acceleration achieves performance nearly three times faster than software couterparts [Jin22, pp. 41–42]. When using the WolfSSL library with the fastmath library, benchmarks indicate that the SHA Accelerator operates more than eight times faster than its software counterpart. Thus, the SHA Accelerator is an effective solution for speeding up SHA-256 hashing operations on the ESP32.

3.2.6. RSA Accelerator

ElectionGuard's decision to use integer ElGamal instead of elliptic-curve ElGamal was driven by its conceptual simplicity and lower implementation barrier [Ben+24, p. 7]. While elliptic-curve cryptographic Elliptic Curve Cryptography (ECC) techniques offer computational advantages, such as reduced computing requirements and smaller key sizes for the same security level [Sag12, pp. 1, 6], the integer ElGamal approach aligns well with the ESP32 hardware. This is because the RSA algorithm, like integer ElGamal, relies on large integer arithmetic. Specifically, the ESP32 chip supports independent arithmetic operations, including large-number multiplication, large-number modular multiplication, and large-number modular exponentiation [25b, p. 32] [25c, p. 603]. Consequently, the RSA Accelerator can accelerate two key operations: modular multiplication and the computationally intensive modular exponentiation. However, modular addition cannot be accelerated using dedicated hardware and must rely on a software implementation.

The RSA Accelerator supports eight operand lengths for modular exponentiation and modular multiplication, including the reduced 3072-bit and even the 4096-bit baseline parameters used in our implementation [25c, p. 598]. The large-number

modular exponentiation operation computes $Z = X^Y M$, while the large-number modular multiplication operation computes $Z = X \times YM$. Both operations are based on Montgomery multiplication. In addition to the input arguments X, Y, and M, two additional arguments are required: the Montgomery Inverse $\overline{r}$ and the inverse of M'. These additional arguments are precomputed by software [25c, pp. 598–599].

The wolfSSL library defaults to a software implementation for smaller operands, whereas the mbedTLS library lacks such a fallback mechanism. Interestingly, using hardware acceleration for small operands can be less efficient than a software implementation. For example, in one test, the mbedTLS modular exponentiation function with hardware acceleration was 1.44 times slower for small operands but 12.84 times faster for large operands [Jin22, p. 51]. This inefficiency for small operands likely stems from the initialization overhead of the hardware accelerator, which outweighs the benefits for smaller values. However, the mbedTLS library provides functions that allow caching of the $\overline{r}$-inverse and M'-inverse values, which can significantly speed up operations [Jin22, p. 51]. Since calculating the $\overline{r}$-inverse is computationally expensive, precomputing and caching these values can enhance performance [Jin22, p. 51].

In our implementation, the modular exponentiation function switches to a software implementation for small values, as shown in Appendix A.2.4. This switch occurs during polynomial calculations, where the number of polynomials (starting from 0 and incrementing) is used as the exponent in the modular exponentiation operation. The polynomial function is detailed in Appendix A.2.4.

In summary, the RSA Accelerator effectively accelerates modular exponentiation and modular multiplication in the ElectionGuard implementation. The mbedTLS library offers efficiency gains through caching of the $\overline{r}$-inverse and M'-inverse values. However, its lack of a fallback mechanism for small operands necessitates an additional software implementation to avoid inefficiencies when using the RSA Accelerator with small values.

3.3. Communication

A sequence diagram of the pre-election steps are seen in 3.3a. In it we see that the Election administrator sends ceremony details to the Guardians and receives a joint key in return. The joint key is then loaded into the encryption devices. In order to generate a joint key each guardian send their public key to a receiving guardians. The receiving guardian generates a designated backup for each guardian. If a guardian receives a designated backup the included proofs are verified. If a proof

failed the guardian send the unverified backup to other guardians as a challenge. If the proof fails again this guardian that generated the backup is evicted and the ceremony has to be restarted.

A sequence diagram of the intra-election steps is seen in 3.3b. The election administrator would need an empty ballot to the voter. A voter then sends their filled ballot to the encryption device. The encryption devices sends back a verification code. The voter can then decide to either cast or spoil the ballot associated with the verification code. If the voter decides to spoil the ballot the encryption devices needs to mark the encrypted ballot as spoiled and the process starts a new. The loop is broken if the voter decides to cast a ballot.

In the post-election steps the encryption device generates a decrypted tally from all cast encrypted ballots and send the encrypted tally to the guardians. If all guardians are present each guardian generates a decryption share which is combined to a decrypted tally. This decrypted tally is then send back to the administrator. If guardians are missing the guardians in addition to generating their decryption share have to compensate for the missing guardians. Missing decryption shares are reconstructed from the backups generated in the pre-election phase. Finally all decryption shares including the reconstructed shares are combined into a decrypted tally. The decrypted tally is then send back to the administrator. Optionally the spoiled ballots can be decrypted through the same mechanisms as the encrypted tally. At the end of the election the administratir publishes all election artifacts to the public for scrutiny.

IoT systems rely primarily on using messaging protocols for exchanging IoT data and there exists several protocols or frameworks that support distinct types of messaging patterns Given that IoT devices typically have limited computational resources and processing power, choosing a lightweight, reliable, scalable, interoperable, extensible and secure messaging protocol becomes a very challenging task. [Al-+20, p. 1].

3.3.1. Data Scheme

3.3.2. Data Link Layer Protocols

When choosing a suitable messaging protocol, it is imperative to consider the hardware characteristics of IoT devices and type of data link layer protocols employed [Al-+20, pp. 1–2]. The data link layer is responsible for data transfers between network entities [Al-+20, p. 3]. The ESP32 supports Wi-Fi and Bluetooth data link layer protocols. The Bluetooth system on the ESP32 can be further divided into Classic Bluetooth and BLE [25a] []. Both Wi-Fi and Bluetooth can coexist but

would require time sharing control [].

Wi-Fi (802.11n) generally has a higher transmission range of approximately 1 km compared to BLE, which has a range of approximately 100 m [Al-+20, p. 3]. The transmission throughput of WiFi is generally higher compared to the transmission throughout of BLE [Al-+20, p. 3]. However, IoT devices can vary significantly in terms of the bandwidth they support. IoT devices do not use a universal radio technology, and therefore, the physical data rate they support varies considerably depending on the size and hardware components used to build these devices [Al-+20, pp. 1–2]. The throughput additionaly depends on various factors such as environmental interference, connection interval, and MTU size. The maximum BLE throughput achievable on the ESP32 is about 90 KB/s, for Classic Bluetooth is about 200 KB/s, and for Wi-Fi it is about 20 MBit/s TCP and 30 MBits/ UDP [25a] [].

In addition to these data link layer protocols, there are also a plethora of custom protocols at the data link layer. The Wi-Fi and BLE stacks also support Mesh Networking, which enables many-to-many device communications and is optimized for creating large-scale device networks [25a]. The Wi-Fi stack additionally supports Wi-Fi Neighbor Awareness Networking (NAN), which allows device-to-device communication directly between two devices. The ESP32 also supports the proprietary protocol ESP-NOW, which allows for connectionless device-to-device communication between ESP32 devices [25a].

Understanding protocols at the data link layer is not sufficient to build IoT applications. It is essential to also consider protocols that exist at the application level, complementing those at the data link layer [Al-+20, p. 2]. Carefully choosing a protocol closer to the application layer while also considering crucial system requirements such as Quality of Service, bandwidth, interoperability, and security becomes inevitable [Al-+20, p. 2].

3.3.3. Application Layer Protocols

When developing IoT systems, choosing the most appropriate Messaging Protocols becomes a challenging task [Al-+20, p. 2]. Although all messaging protocols are used for data communication between two or more entities via some transmission medium, some of the characteristics of each protocol vary [Al-+20, p. 15]. To identify a suitable protocol requires sufficient background knowledge on how these protocols operate and how to overcome challenges that may arise [Al-+20, pp. 2, 15]. A suitable messaging protocol helps reduce network traffic and latency and thus increases an IoT application's reliability [Al-+20, p. 2]. For example, using application layer protocols that are capable of capturing data much faster than actual physical data rates often leads to high latency. Therefore, it would be desirable when developing

IoT applications to consider messaging protocols that can accommodate or support physical data rates at the data link layer [Al-+20, p. 2].

The application layer is an abstraction layer [Al-+20, p. 3]. Within ESP32 exists several application layer protocols that address a wide range of application requirements. Each of these protocols provide various features that vary in terms of reliability, quality of service, performance, functionality and scalability, among other factors. [Al-+20, p. 3]. Some of the protocols that exist as components of the ESP32 at the application layer include: HyperText Transfer Protocol (HTTP), Secure HTTP (HTTPS), Message Queueing Telemetry Transport (MQTT) over TCP, MQTT over Websocket [25a]. In addition, industry specific protocols used primarily in industrial IoT environments also exist such as Modbus [Al-+20, p. 3]. And ESP32 also provides support for the proprietary protocol ESP-NOW [25a].

Choosing an appropriate messaging protocol depends on a number of factors including IoT application's software capabilities, device or hardware capabilities, and average size of data exchanges, among many others. [Al-+20, p. 2].

ESP32-Now has a communication scope of device-to-device communication meaning we could use this protocol for the communication between ESP32 devices. A communication between Guardians during the key exchange would thus be possible however the communication between the Election Administrator and the Guardians would not be possible. The communication between Guardian is also not suitable. ESP-Now limits the data payload to 250 bytes [25a]. This is unstuitable considering that sending a single public key is already 384 bytes (3072 bit key).

The maximum packet size for ESP BLE Mesh transmission is 384 bytes []. And the maximum packet size for Wi-Fi Mesh data transmission is 1,456 bytes. []. The Wi-Fi Mesh data transmission rate is also too small. The minimum package size for a public key without any additional coefficients (yellow) and without the private key (red) send by a guardian is 1642 bytes. The message scheme is seen in figure. 3.4. Each additional coefficients adds 1248 bytes to the message. This is largely due to large commitment sizes. MQTT has a maximum payload size of 256 MB and HTTP does not define a maximum message size. The message size is thus not a limiting factor for MQTT and HTTP protocols.

HTTP is an generic, stateless request-response protocol in which a client sends a request message and a server generates a response message [Al-+20, p. 8]. Inside our network we would need to utilize something like multicast DNS (mDNS) for example in order to discover the services in our network (e.g. other guardians or the election administrator). [Al-+20, p. 20]

Message reliability is imperative in this publish- subscribe brokering model. That is, an IoT system may require that messages be delivered in a reliable manner where

all clients acknowledge the receipt of these messages. MQTT supports a Quality of Service (QoS) level when messages are published through the Connect Flags of the Fixed Header using the Will QoS parameter (bits 4 and 3). These bits specify the QoS level applied when a broker publishes a message to one or more clients. MQTT supports three levels of QoS as presented in Table VI. [Al-+20, p. 11] As shown in Table VI, as the QoS level increases, the reliability of messages' delivery also increases. However, this also increases the overhead associated with ensuring that all clients receive the intended messages. The more clients are subscribed to receive a message with QoS 2, for example, will increase the overhead on the message broker while ensuring the delivery of the message without duplication or retransmission. [Al-+20, p. 11] The MQTT handling of disallowed Unicode code points provides a client or server the option to decide on the validation of these code points (e.g. UTF-8 encoded strings). As a result, an endpoint does not necessarily need to validate UTF-8 encoded strings (e.g. topic name or property). As such, a client could potentially use this as a vulnerability and causes a subscribed client to close the network connection using a topic that contains an invalid Unicode code point. A malicious client can then use this as a security exploit for possibly causing a Denial of Service (DoS) attack. Therefore, enabling UTF-8 encoded strings, for example, can allow these security exploits to occur in cases they are used as control characters or in control packets (see the first [Al-+20, p. 11]

QoS 0 lowest at most once delivery - no response is sent by receiver, no retry is performed by sender - message arrives at the receiver either once or not at all QoS 1 medium at least once delivery - ensures that a message arrives at the receiver at least once - receiver may send further PUBLISH packets while waiting to receive acknowledgments QoS 2 highest exactly once delivery - ensures that a message arrives at the receiver exactly once without duplication - increased overhead associated with this level [Al-+20, p. 11]

3.3.4. MQTT's role in IoT

MQTT is an asynchronous lightweight publish/subscribe messaging protocol designed for Machine-to-Machine (M2M) communication [Al-+20, p. 2]. It is designed to handle situations in case of unreliable networks or intermittent connectivity, and enables the exchange of data in a real-time manner [Al-+20, p. 10].

MQTT is composed of a broker and clients establish a connection with the broker at any time. In this model, clients send messages through the broker which is known as the publisher. Then, the broker filters these incoming messages and distributes them to clients who are interested in receiving these messages. To this extent, a client that registers with the broker to receive these messages must first subscribe to specific topics. Clients receive the payload when a new device publishes a message.

A subscriber can receive a published message later. That is, the subscribers can receive published messages at different times. In this publish-subscribe model, a publisher can send messages to a number of subscribers with one single publish operation to the broker. The broker handles the "broadcasting" or sending messages to all subscribers subscribed to topic of the message

Figure 9 presents a high-level overview of the MQTT brokering model that shows all of the entities involved in this architecture including: (a) centralized broker, (b) publishers and (c) subscribers. [Al-+20, p. 10] as shown in Figure 9.

There are a number of MQTT model implementations including Mosquitto, eMQTT, HiveMQ, Moquette, among many others. [Al-+20, p. 10]

For MQTT dicovery is based on topics [Al-+20, p. 27]

3.3.5. Comparison MQTT vs HTTP

MQTT is considered lighter than HTTP 1.1 and supports a near real-time message exchange [Al-+20, p. 10]

HTTP may not be an ideal choice for a messaging protocol for data connectivity [Al-+20, p. 15].

Furthermore, when choosing a message protocol such as MQTT, the number of message transmissions increases significantly as more clients subscribe to topics. [Al-+20, p. 19]

The case can become worse if the broker's resources are maximized and hence a broker becomes a source for a Single Point of Failure (SPoF). Because MQTT is designed primarily for a Device-to-Cloud (D2C) communication scope, the problem of SPoF can be resolved by serverless computing which increases the agility of the deployed IoT application [Al-+20, p. 19]

MQTT is D2C communication scope, the further these nodes are from the deployed serverless solution in terms of distance, the longer is the travel time of the MQTT messages and the higher the latency [Al-+20, p. 20]

However, existing implementations of MQTT vary in terms of performance and scalability. In [111], the authors compared Mosquitto, HiveMQ and BevyWise MQTT broker deployed on the cloud [Al-+20, p. 20]

There are a number of studies that have examined the performance and scalability of

communication protocols. Some studies have found that the throughput in MQTT drops significantly as the number of clients' subscriptions increases [112, 113]. In [114], the authors compared the performance of DDS and MQTT. [Al-+20, p. 21]

The performance and scalability of messaging protocols vary. CoAP and HTTP have an additional overhead associated with transporting messages. CoAP and HTTP should be used in cases where low latency is not of critical importance. Hence, this makes these two protocols not very suitable for real-time IoT edge- or fog-based systems. MQTT follows a device-to-cloud data flow and therefore introduces network latency dependent on the cloud service performance. [Al-+20, p. 21]

Generally, message brokers may deliver 100 to 1000 messages per second per subscriber [20, 117]. However, these messaging brokers can vary significantly.

esults in Section V.D which suggested that the performance of MQTT in terms of latency degrades significantly as the number of messages increases. [Al-+20, p. 22]

In addition, MQTT used the least power consumption in delivering large volumes of messages compared to CoAP and HTTP. [Al-+20, p. 22]

MQTT had the least power consumption in terms of battery life followed by CoAP and then HTTP. That is, HTTP had 5.3 times the power consumption of that of MQTT and 2.8 times the power consumption of that of CoAP [Al-+20, p. 23]

Furthermore, IoT devices are generally used by humans which makes them vulnerable to intruders that attempt to gain unsolicited access or collect confidential personal data in a malicious manner. [Al-+20, p. 23]

An IoT communication protocol needs to ensure that only authorized users regardless if they are publishers or subscribers Furthermore, such vulnerabilities may occur when offering QoS level 2 which may explain why many IoT cloud providers not to provide support at this level as presented in Table VII. Although each protocol provides different levels of security measure[Al-+20, p. 23]

Although HTTP remains to be among the top two protocols across all years, there is an apparent drop in its usage with approximately 9in Figure 21. On the contrary, MQTT has witnessed a significant increase in its usage from 2017 to 2018. The survey results from the 2019 Eclipse Foundation and Eclipse IoT Working Group is partial but report that HTTP and MQTT remain among the top three messaging protocols [156]. In addition, the AMQP protocol has been witnessing a gradual increase over the years in terms of its usage by developers who have completed the surveys and as illustrated in Figure 21. DDS remains steady at the same rate while CoAP has witnessed a slight decline between 2017 and 2018. In the results from the 2019 survey, the report show that CoAP has dropped below a 15[Al-+20, p. 26]

HTTP Advantages: uses a push approach which involves a persistent connection between client and server Disadvantages: header size is large: this adds processing overhead for devices particularly constrained IoT devices high network latency: this makes the protocol not suitable for real-time or mission-critical IoT systems uses text not binary encoding protocol does not provide any QoS support protocol is not easily scalable computational overhead due to encrypting and decrypting (secure) messages [Al-+20, p. 26]

MQTT Advantages: has a transient data message transmission cycle good for cloud-based IoT applications (D2C) a lightweight protocol and works fairly well over constrained networks provides an adequate level of QoS support (0, 1, 2) protocol supports asynchronous messaging protocol is an event-driven which enables an IoT system to scale up (or down) protocol can be used for M2M communication supported by many IoT cloud providers (Table III) Disadvantages: does not support large payloads topic names are often long; inappropriate for low-rate wireless personal area networks (LR-WPANs) unsuitable for IoT devices that require sending multimedia content (e.g. audio, images or videos) protocol is not suitable for device-to-device communication (suitable for device-to-cloud only) lack of encryption; can use TLS/SSL for security and encryption, however, extra connection overhead no dynamic discovery (discovery based on topics) and broker can be a Single Point of Failure (SPoF) MQTT clients needs to support TCP; connections remain open with brokers (always on); limited sleep mode for constrained devices [Al-+20, p. 27]

3.3.6. Serialization

3.3.7. Data serialization

Data serialization is the process of structuring data into a streamlined format before storing or transmitting it. Broadly speaking, there are two approaches to serialization: text-based and binary. In text-based serialization, data is typically structured into key-value pairs in a readable text format. In binary serialization, key-value pairs are stored in a binary format, which typically reduces space requirements [PC20, p. 11]. The design specification of ElectionGuard does not specify serialization methods or data structures. However, every implementation of ElectionGuard should be compatible with other implementations [Ben+24, p. 23]. The Python implementation expects data to be serialized into the text-based JSON format.

Exchanging data in different formats across IoT devices raises syntactic interoperability issues that need to be addressed [Al-+20, p. 17]. However, if we want to transmit data through the network faster, smaller data sizes are preferable. Addi-

tionally, the data does not need to be human-readable during transmission like with text-based formats [Cur22, p. 225]. Binary formats are typically preferred as they provide smaller message sizes compared to text-based formats like JSON [PC20, p. 11]. For instance, in a test using ESP32, the encoding size was, on average, smaller for Protocol Buffers (a binary format) compared to the text-based JSON format [Lui+21, p. 15]. Thus we could use a binary format for sending data over the network to reduce the message size however we would need to convert the data into a JSON format for the Python implementation.

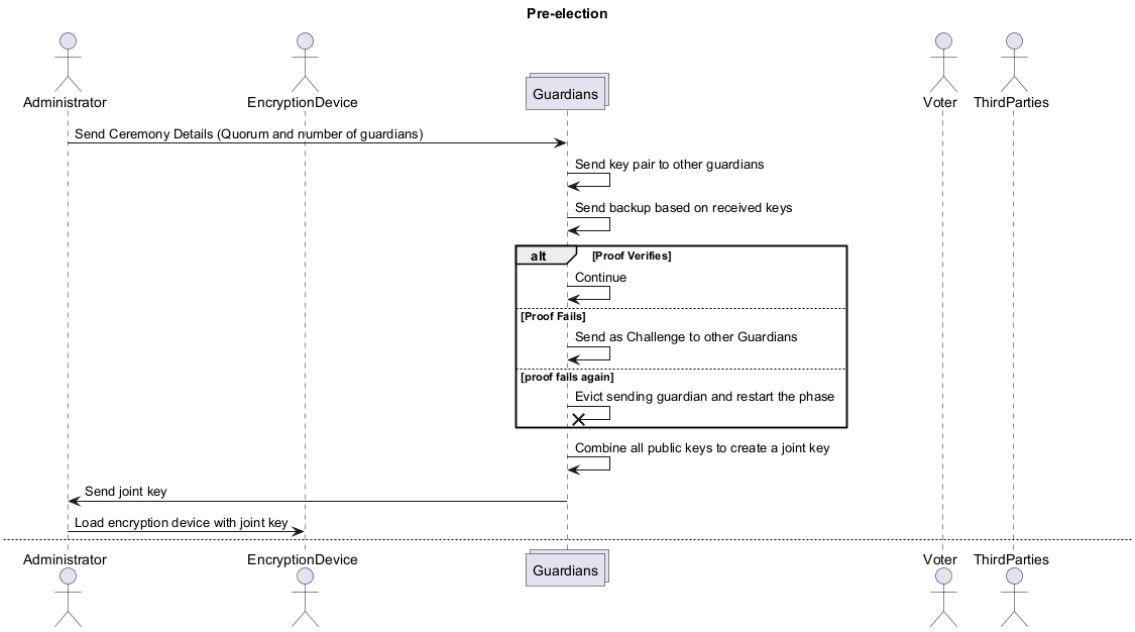
Another benefit of more efficient formats is improved serialization and deserialization speeds. This indicates that fewer CPU cycles are used for data processing, leading to lower power consumption. In one test on the ESP32, the serialization and deserialization speed was almost halved when using Protocol Buffers compared to JSON [Lui+21, pp. 11–12].

In our case, choosing a binary serialization approach could be beneficial. The in-memory data representation of our data structures in the ESP32 implementation uses structs, as seen in Appendix A.2.5. These structures contain a custom data type, $\mathrm{sp}_i nt, which is a large integer representation. To parse the large integer into a hexadecimal JSON$

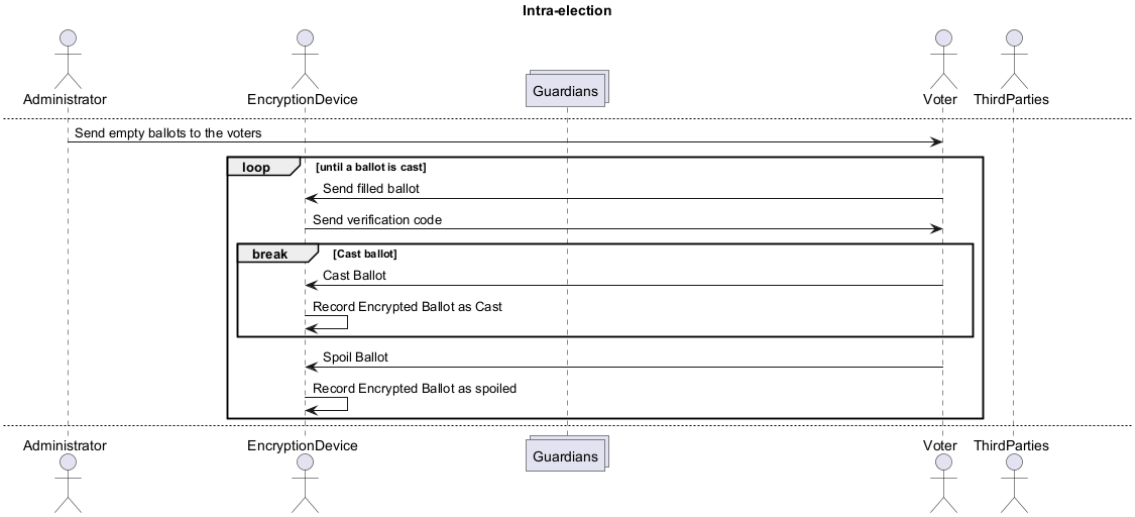
Our implementation, therefore, chooses Protocol Buffers as the serialization format. A Protocol Buffer implementation is already included in the ESP32 as a component. A significant advantage of Protocol Buffers is that we only need to define the structure for the data to be transferred once and can then exchange it over a wide variety of channels. The programming language is secondary since Protocol Buffers are language-neutral **proto**. Thus, with our .proto files, as seen in Appendix **??**, we can generate code for both the ESP32 and the Python client, as seen in Appendices A.3.4 and A.3.4. An example of serialising ElectionPartialKeyPair which is the backup shared with other guardians is seen in Appendix A.3.1 an example of deserialisation is seen in Appendix A.3.2.

3.4. Usability

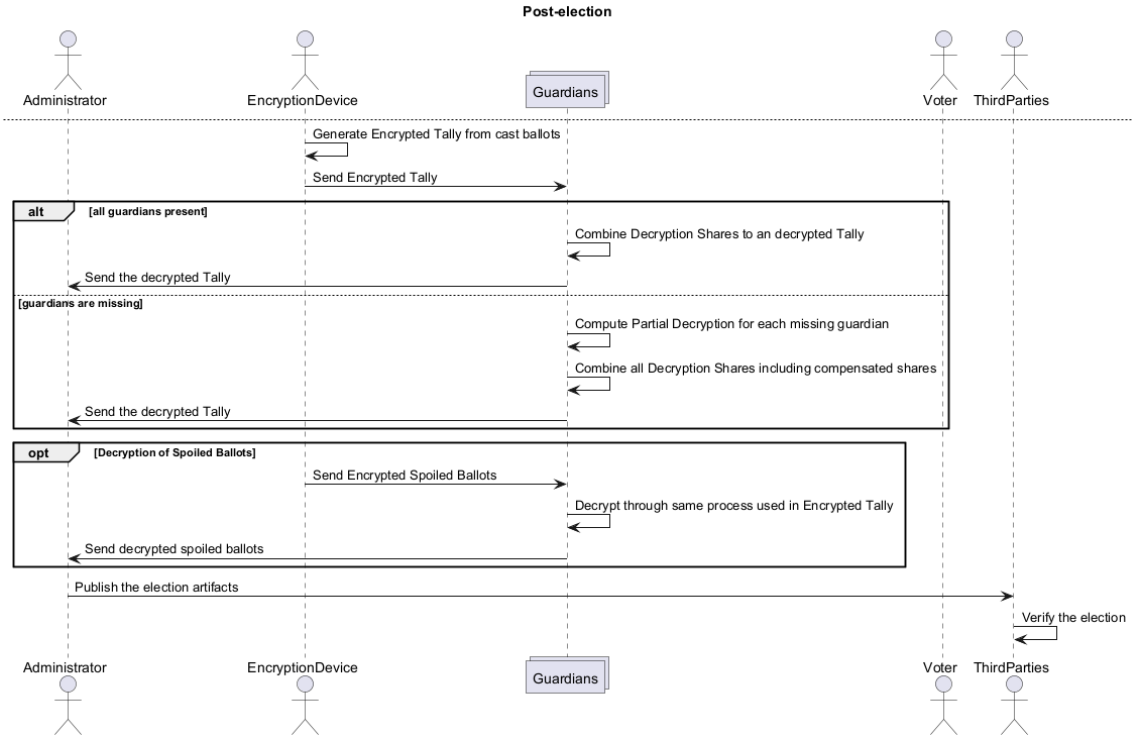
Graphics Library: lvgl



(a) Communication Sequence in the Pre-election phase



(b) Communication Sequence in the Intra-election phase



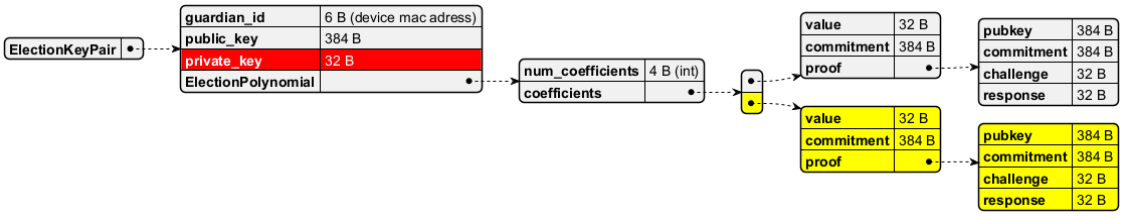


Figure 3.4.: Key Pair message size

4. Conclusions

Im Schlusskapitel wird die Arbeit und ihre Ergebnisse zusammengefasst sowie ein Ausblick gegeben.

List of Figures

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A. Appendix

A.1. wolfSSL

A.1.1. User Settings

```
#define NO_SESSION_CACHE

/* Small Stack uses more heap. */
#define WOLFSSL_SMALL_STACK
```

```
#define RSA_LOW_MEM

// * FP_MAX_BITS defaults to 4096 bits. This allows only
   multiplication of up to 2048x2048 bits.
#define FP_MAX_BITS 6144
```

```
/* adjust wait-timeout count if you see timeout in RSA HW
   acceleration */
#define ESP_RSA_TIMEOUT_CNT    0x349F00

/* hash limit for test.c */
#define HASH_SIZE_LIMIT

/* USE_FAST_MATH is default */
#define USE_FAST_MATH

/*****      Use SP_MATH      *****/
#undef USE_FAST_MATH          //+-
#define SP_MATH               //+-
#define WOLFSSL_SP_MATH_ALL   //+-

#define WOLFSSL_SP_SMALL //++
#define WOLFSSL_SP_LOW_MEM //++
#define WOLFSSL_HAVE_SP_RSA //++
#define WOLFSSL_SP_4096 //++
/* #define WOLFSSL_SP_RISCV32    */

/***** Use Integer Heap Math *****/
/* #undef USE_FAST_MATH          */
/* #define USE_INTEGER_HEAP_MATH */
```

```
#define WOLFSSL_SMALL_STACK
```

A.2. Model Component

A.2.1. Cryptographic Constants

```
#include "constants.h"

const unsigned char p_3072[] = {
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0x93, 0xC4, 0x67, 0xE3, 0x7D, 0xB0, 0xC7, 0xA4,
    0xD1, 0xBE, 0x3F, 0x81, 0x01, 0x52, 0xCB, 0x56,
    0xA1, 0xCE, 0xCC, 0x3A, 0xF6, 0x5C, 0xC0, 0x19,
    0x0C, 0x03, 0xDF, 0x34, 0x70, 0x9A, 0xFF, 0xBD,
    0x8E, 0x4B, 0x59, 0xFA, 0x03, 0xA9, 0xF0, 0xEE,
    0xD0, 0x64, 0x9C, 0xCB, 0x62, 0x10, 0x57, 0xD1,
    0x10, 0x56, 0xAE, 0x91, 0x32, 0x13, 0x5A, 0x08,
    0xE4, 0x3B, 0x46, 0x73, 0xD7, 0x4B, 0xAF, 0xEA,
    0x58, 0xDE, 0xB8, 0x78, 0xCC, 0x86, 0xD7, 0x33,
    0xDB, 0xE7, 0xBF, 0x38, 0x15, 0x4B, 0x36, 0xCF,
    0x8A, 0x96, 0xD1, 0x56, 0x78, 0x99, 0xAA, 0xAE,
    0x0C, 0x09, 0xD4, 0xC8, 0xB6, 0xB7, 0xB8, 0x6F,
    0xD2, 0xA1, 0xEA, 0x1D, 0xE6, 0x2F, 0xF8, 0x64,
    0x3E, 0xC7, 0xC2, 0x71, 0x82, 0x79, 0x77, 0x22,
    0x5E, 0x6A, 0xC2, 0xF0, 0xBD, 0x61, 0xC7, 0x46,
    0x96, 0x15, 0x42, 0xA3, 0xCE, 0x3B, 0xEA, 0x5D,
    0xB5, 0x4F, 0xE7, 0x0E, 0x63, 0xE6, 0xD0, 0x9F,
    0x8F, 0xC2, 0x86, 0x58, 0xE8, 0x05, 0x67, 0xA4,
    0x7C, 0xFD, 0xE6, 0x0E, 0xE7, 0x41, 0xE5, 0xD8,
    0x5A, 0x7B, 0xD4, 0x69, 0x31, 0xCE, 0xD8, 0x22,
    0x03, 0x65, 0x59, 0x49, 0x64, 0xB8, 0x39, 0x89,
    0x6F, 0xCA, 0xAB, 0xCC, 0xC9, 0xB3, 0x19, 0x59,
    0xC0, 0x83, 0xF2, 0x2A, 0xD3, 0xEE, 0x59, 0x1C,
    0x32, 0xFA, 0xB2, 0xC7, 0x44, 0x8F, 0x2A, 0x05,
    0x7D, 0xB2, 0xDB, 0x49, 0xEE, 0x52, 0xE0, 0x18,
    0x27, 0x41, 0xE5, 0x38, 0x65, 0xF0, 0x04, 0xCC,
    0x8E, 0x70, 0x4B, 0x7C, 0x5C, 0x40, 0xBF, 0x30,
    0x4C, 0x4D, 0x8C, 0x4F, 0x13, 0xED, 0xF6, 0x04,
    0x7C, 0x55, 0x53, 0x02, 0xD2, 0x23, 0x8D, 0x8C,
    0xE1, 0x1D, 0xF2, 0x42, 0x4F, 0x1B, 0x66, 0xC2,
    0xC5, 0xD2, 0x38, 0xD0, 0x74, 0x4D, 0xB6, 0x79,
    0xAF, 0x28, 0x90, 0x48, 0x70, 0x31, 0xF9, 0xC0,
    0xAE, 0xA1, 0xC4, 0xBB, 0x6F, 0xE9, 0x55, 0x4E,
    0xE5, 0x28, 0xFD, 0xF1, 0xB0, 0x5E, 0x5B, 0x25,
```

```
    0x62, 0x23, 0xB2, 0xF0, 0x92, 0x15, 0xF3, 0x71,
    0x9F, 0x9C, 0x7C, 0xCC, 0x69, 0xDE, 0xD4, 0xE5,
    0x30, 0xA6, 0xEC, 0x94, 0x0C, 0x45, 0x31, 0x4D,
    0x16, 0xD3, 0xD8, 0x64, 0xB4, 0xA8, 0x93, 0x4F,
    0x8B, 0x87, 0xC5, 0x2A, 0xFA, 0x09, 0x61, 0xA0,
    0xA6, 0xC5, 0xEE, 0x4A, 0x35, 0x37, 0x77, 0x73,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF
};


const unsigned char g_3072[] = {
    0xAF, 0x8D, 0xC2, 0x05, 0x79, 0x63, 0xC6, 0xC3,
    0x64, 0x11, 0x9C, 0x01, 0x4A, 0x27, 0x68, 0x6B,
    0xA7, 0x80, 0x57, 0x67, 0x48, 0xB7, 0x2F, 0x67,
    0x0C, 0x4A, 0x5D, 0x4C, 0x3F, 0xAC, 0x1E, 0x22,
    0x8B, 0x84, 0xFB, 0xA8, 0x8C, 0x4E, 0xAF, 0x94,
    0xDF, 0x98, 0x75, 0x5C, 0x6C, 0x73, 0x61, 0x1B,
    0xB5, 0x4A, 0x14, 0xA6, 0xE2, 0x32, 0xD2, 0x38,
    0xC9, 0x17, 0xDA, 0x76, 0xD8, 0xA6, 0x2B, 0x70,
    0x83, 0x7A, 0x15, 0xEE, 0xC1, 0x11, 0x0C, 0x11,
    0x25, 0x61, 0xAB, 0x0E, 0xAE, 0x9E, 0x11, 0xDD,
    0xCE, 0xC6, 0x1F, 0x2B, 0xBD, 0x54, 0xBB, 0x76,
    0x2F, 0xC9, 0x03, 0x49, 0x4E, 0xF2, 0x1F, 0x0F,
    0x33, 0x8F, 0xE2, 0x65, 0x82, 0x45, 0x3C, 0xE3,
    0xFF, 0x02, 0xC5, 0x3A, 0x77, 0x29, 0x61, 0x26,
    0xE5, 0x9E, 0x19, 0x80, 0xCD, 0x49, 0xA5, 0x67,
    0x26, 0xA4, 0x0C, 0xFD, 0xEF, 0x93, 0xA1, 0x81,
    0x41, 0xCF, 0x83, 0x44, 0x2D, 0x0F, 0xDC, 0xDF,
    0x9F, 0x13, 0x51, 0xB2, 0xD0, 0xCF, 0x81, 0x4C,
    0xE9, 0xC7, 0x96, 0x40, 0x2D, 0xC2, 0x21, 0x81,
    0x32, 0xD2, 0x83, 0x60, 0x5B, 0xDD, 0x15, 0x46,
    0x8E, 0xAB, 0xA4, 0xB6, 0xF7, 0x8E, 0x4D, 0xE3,
    0xDE, 0x07, 0x66, 0xFA, 0x99, 0x15, 0xED, 0x28,
    0xE0, 0x0D, 0x90, 0x75, 0x7F, 0x49, 0x49, 0x86,
    0x09, 0x24, 0x77, 0xC9, 0x0C, 0x5F, 0xC3, 0x05,
    0xA5, 0x68, 0x29, 0x08, 0x8D, 0x99, 0x6D, 0x22,
    0x7D, 0x2F, 0x01, 0x8C, 0x1A, 0x16, 0x37, 0x7B,
    0x00, 0x14, 0xA8, 0x18, 0x3F, 0x59, 0xCF, 0x88,
    0x71, 0xC4, 0x65, 0x91, 0x32, 0xBD, 0xDB, 0xA7,
    0x9E, 0x86, 0x9A, 0xE8, 0xF6, 0x5C, 0x93, 0x60,
    0x8D, 0x17, 0x9A, 0x07, 0xD7, 0xD9, 0x94, 0xE0,
    0x58, 0xE5, 0xF5, 0x1B, 0x47, 0xC7, 0x20, 0x9A,
    0x25, 0x86, 0x4D, 0xA9, 0xF1, 0x37, 0x7C, 0x16,
    0xB1, 0xC0, 0x9C, 0x85, 0xB6, 0x6C, 0xC3, 0xD5,
    0x27, 0xFA, 0xB3, 0xF6, 0xB2, 0xDF, 0x6D, 0x6B,
    0xEA, 0x15, 0x20, 0x62, 0x98, 0xBA, 0xC3, 0xE2,
    0x93, 0xF1, 0x0E, 0x2E, 0x9B, 0x78, 0x0E, 0xCE,
    0x03, 0x3A, 0x47, 0xCF, 0xC4, 0x51, 0x22, 0x15,
    0x22, 0xBB, 0x70, 0x9E, 0x1B, 0x94, 0xD8, 0xEA,
```

```
    0x74, 0x87, 0x24, 0x21, 0x85, 0xD8, 0xF8, 0xFB,
    0x01, 0x3E, 0x9E, 0x10, 0x73, 0x95, 0xD5, 0x3E,
    0x22, 0xC5, 0x55, 0x02, 0xFC, 0x1E, 0x4A, 0x91,
    0x57, 0x66, 0xF3, 0xC3, 0xB4, 0x63, 0xA3, 0xEE,
    0x4C, 0xB6, 0x82, 0x92, 0x6A, 0x0C, 0x4F, 0x87,
    0xCD, 0x86, 0x18, 0x1A, 0xBC, 0x6F, 0xB9, 0x02,
    0xBD, 0x83, 0x31, 0xDE, 0x18, 0xF5, 0x98, 0x20,
    0xC5, 0xD9, 0x67, 0xD7, 0x84, 0xB1, 0xC0, 0x6E,
    0x5A, 0x94, 0xF3, 0x1E, 0xF8, 0x61, 0x1B, 0x54,
    0x5D, 0x2F, 0x1E, 0x18, 0x4C, 0xEA, 0xC3, 0x12
};

const unsigned char q_256[] = {
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF,
    0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0xFF, 0x43
};
```

A.2.2. RNG

```
/**
 * @brief Generate a random number below Q
 * Q is very close to the maximum value for a 256 bit number. It
    might be worth to compare and regenerate in case mod is
    expensive
 * @param result: The random number
 * @return 0 on success, -1 on failure
 */
int rand_q(sp_int *result) {
    DECL_MP_INT_SIZE(small_prime, 256);
    NEW_MP_INT_SIZE(small_prime, 256, NULL, DYNAMIC_TYPE_BIGINT);
    INIT_MP_INT_SIZE(small_prime, 256);
    sp_read_unsigned_bin(small_prime, q_256, sizeof(q_256));

    int sz = 32;
    unsigned char *block = (unsigned char *)malloc(sz * sizeof(
       unsigned char));
    if (block == NULL) {
        ESP_LOGE("RAND_Q", "Failed to allocate memory for block");
        return -1; // Memory allocation failed
    }

    esp_fill_random(block, sz);
    sp_read_unsigned_bin(result, block, sz);
    sp_mod(result, small_prime, result);

    // Clear
    memset(block, 0, sz);
    free(block);
    FREE_MP_INT_SIZE(small_prime, NULL, DYNAMIC_TYPE_BIGINT);
```

```
    return 0;
}
```

A.2.3. Hash Functions

```
/**
 * @brief Given two mp_ints, calculate their cryptographic hash
    using SHA256.
 * Possible collision. In the python implementation a delimiter (|)
     is used
 * @param a: First element
 * @param b: Second element
 * @param result: The result of the hash
 * @return 0 on success, -1 on failure
 */
int hash(sp_int *a, sp_int *b, sp_int *result) {
    int ret;
    word32 a_size = sp_unsigned_bin_size(a);
    word32 b_size = sp_unsigned_bin_size(b);
    word32 tmp_size = a_size + b_size;
    ESP_LOGI("HASH_ELEMS", "a_size: %d, b_size: %d, tmp_size: %d",
       a_size, b_size, tmp_size);

    byte *tmp = (byte *)malloc(tmp_size);
    if (tmp == NULL) {
        ESP_LOGE("HASH_ELEMS", "Failed to allocate memory for tmp")
           ;
        return -1; // Return an error code
    }
    // Concatenate the two mp_ints
    ret = sp_to_unsigned_bin_at_pos(0, a, tmp);
    ret = sp_to_unsigned_bin_at_pos(a_size,b, tmp);

    byte *result_byte = (byte *)malloc(WC_SHA256_DIGEST_SIZE);
    if (result_byte == NULL) {
        ESP_LOGE("HASH_ELEMS", "Failed to allocate memory for
           result_byte");
        return -1; // Return an error code
    }

    // Conveniencefunction. Handles Initialisation, Update and
       Finalisation
    if ((ret = wc_Sha256Hash(tmp, tmp_size, result_byte)) != 0) {
        WOLFSSL_MSG("Hashing Failed");
        return ret;
    }

    ret = sp_read_unsigned_bin(result, result_byte,
       WC_SHA256_DIGEST_SIZE);
    free(tmp);
    free(result_byte);
```

```
    return ret;
}
```

```
/**
 * @brief Get a hash-based message authentication code(hmac) digest
 * @param key: key (key) in bytes
 * @return error_code
 */
int get_hmac(unsigned char *key, unsigned char *in, unsigned char *
    out) {
    Hmac hmac;
    // Initialise HMAC as SHA256
    if(wc_HmacSetKey(&hmac, WC_SHA256, key, sizeof(key)) != 0) {
        ESP_LOGE("HMAC", "Failed to initialise hmac");
        wc_HmacFree(&hmac);
        return -1;
    }
    if(wc_HmacUpdate(&hmac, in, sizeof(in)) != 0) {
        ESP_LOGE("HMAC", "Failed to update data");
        wc_HmacFree(&hmac);
        return -1;
    }
    if(wc_HmacFinal(&hmac, out) != 0) {
        ESP_LOGE("HMAC", "Failed to compute hash");
        wc_HmacFree(&hmac);
        return -1;
    }
    wc_HmacFree(&hmac);
    return 0;
}
```

A.2.4. RSA Accelerator

```
/**
 * @brief Compute Large number Modular Exponetiation with hardware
    Y = (G ^ X) mod P. If the inputs are to small switches to
    unaccelerated version
 * @param g: Base
 * @param x: Exponent
 * @param p: Modulus
 * @param y: Result
 * @return 0 on success, -1 on failure
 */
static int exptmod(sp_int *g, sp_int *x, sp_int *p, sp_int *y) {
    int ret;
    ret = esp_mp_exptmod(g,x,p,y);
    if(ret == INPUT_CASE_ERROR) {
        ESP_LOGI("MODEXPT", "Input are too small switching to
            software exptmod");
        ret = sp_exptmod(g,x,p,y);
        if (ret != MP_OKAY) {
            ESP_LOGE("MULMOD", "Error code: %d", ret);
```

```
            return -1;
        }
    }
    return ret;
}
```

```
int compute_polynomial_coordinate(uint8_t* exponent_modifier,
    ElectionPolynomial* polynomial, sp_int *coordinate) {
    DECL_MP_INT_SIZE(modifier, 48);
    NEW_MP_INT_SIZE(modifier, 48, NULL, DYNAMIC_TYPE_BIGINT);
    INIT_MP_INT_SIZE(modifier, 48);
    sp_read_unsigned_bin(modifier, exponent_modifier, sizeof(
        exponent_modifier));

    DECL_MP_INT_SIZE(exponent_i, 48);
    NEW_MP_INT_SIZE(exponent_i, 48, NULL, DYNAMIC_TYPE_BIGINT);
    INIT_MP_INT_SIZE(exponent_i, 48);

    DECL_MP_INT_SIZE(exponent, 256);
    NEW_MP_INT_SIZE(exponent, 256, NULL, DYNAMIC_TYPE_BIGINT);
    INIT_MP_INT_SIZE(exponent, 256);

    DECL_MP_INT_SIZE(factor, 256);
    NEW_MP_INT_SIZE(factor, 256, NULL, DYNAMIC_TYPE_BIGINT);
    INIT_MP_INT_SIZE(factor, 256);

    DECL_MP_INT_SIZE(small_prime, 256);
    NEW_MP_INT_SIZE(small_prime, 256, NULL, DYNAMIC_TYPE_BIGINT);
    INIT_MP_INT_SIZE(small_prime, 256);
    sp_read_unsigned_bin(small_prime, q_256, sizeof(q_256));
    for (size_t i = 0; i < polynomial->num_coefficients; i++)
    {
        sp_set_int(exponent_i, i);
        // Not Accelerated. Operator lenght to small
        exptmod(modifier, exponent_i, small_prime, exponent);
        sp_mulmod(polynomial->coefficients[i].value, exponent,
            small_prime, factor);
        sp_addmod(coordinate, factor, small_prime, coordinate);
    }
    FREE_MP_INT_SIZE(exponent_i, NULL, DYNAMIC_TYPE_BIGINT);
    FREE_MP_INT_SIZE(modifier, NULL, DYNAMIC_TYPE_BIGINT);
    FREE_MP_INT_SIZE(small_prime, NULL, DYNAMIC_TYPE_BIGINT);
    FREE_MP_INT_SIZE(exponent, NULL, DYNAMIC_TYPE_BIGINT);
    FREE_MP_INT_SIZE(factor, NULL, DYNAMIC_TYPE_BIGINT);
    return 0;
}
```

A.2.5. Data Structures

```
typedef struct {
    sp_int* pubkey;
    sp_int* commitment;
```

```
    sp_int* challenge;
    sp_int* response;
} SchnorrProof;

typedef struct {
    sp_int* value;
    sp_int* commitment;
    SchnorrProof proof;
} Coefficient;

typedef struct {
    int num_coefficients;
    Coefficient* coefficients;
} ElectionPolynomial;

// contains also private key. Be careful when sending!
typedef struct {
    uint8_t guardian_id[6];
    sp_int* public_key;
    sp_int* private_key;
    ElectionPolynomial polynomial;
} ElectionKeyPair;

 typedef struct {
    sp_int* pad;
    sp_int* data;
    sp_int* mac;
} HashedElGamalCiphertext;

 typedef struct {
    uint8_t sender[6];
    uint8_t receiver[6];
    HashedElGamalCiphertext encrypted_coordinate;
 } ElectionPartialKeyPairBackup;


 typedef struct {
    uint8_t sender[6];
    uint8_t receiver[6];
    uint8_t verifier[6];
    bool verified;
 } ElectionPartialKeyVerification;

 typedef struct {
    sp_int* joint_key;
    sp_int* commitment_hash;
 } ElectionJointKey;

typedef struct {
    char* object_id;
        sp_int* ciphertext_pad;
        sp_int* ciphertext_data;
```

```
} CiphertextTallySelection;

typedef struct {
    char* object_id;
    int sequence_order;
    sp_int* description_hash;
    int num_selections;
    CiphertextTallySelection* selections;
} CiphertextTallyContest;

typedef struct{
    char* object_id;
    sp_int* base_hash;
    int num_contest;
    CiphertextTallyContest* contests;
} CiphertextTally;

typedef struct {
    sp_int* pad;
    sp_int* data;
    sp_int* challenge;
    sp_int* response;
} ChaumPedersenProof;

typedef struct {
    char* object_id;
    uint8_t guardian_id[6];
    sp_int* decryption;
    ChaumPedersenProof proof;
} CiphertextDecryptionSelection;

typedef struct{
    char* object_id;
    uint8_t guardian_id[6];
    sp_int *public_key;
    sp_int* description_hash;
    int num_selections;
    CiphertextDecryptionSelection* selections;
} CiphertextDecryptionContest;

typedef struct {
    char* object_id;
    uint8_t guardian_id[6];
    sp_int* public_key;
    int num_contest;
    CiphertextDecryptionContest* contests;
} DecryptionShare;
```

A.3. Adapter Component

A.3.1. Serialization

```
uint8_t* serialize_election_partial_key_backup(
    ElectionPartialKeyPairBackup* backup, unsigned* len) {
     ElectionPartialKeyPairBackupProto proto =
        ELECTION_PARTIAL_KEY_PAIR_BACKUP_PROTO__INIT;
     proto.sender.len = sizeof(backup->sender);
     proto.sender.data = backup->sender;
     proto.receiver.len = sizeof(backup->receiver);
     proto.receiver.data = backup->receiver;

     HashedElGamalCiphertextProto hash =
        HASHED_EL_GAMAL_CIPHERTEXT_PROTO__INIT;
     hash.pad.len = sp_unsigned_bin_size(backup->
        encrypted_coordinate.pad);
     hash.pad.data = (uint8_t*)malloc(hash.pad.len);
     sp_to_unsigned_bin(backup->encrypted_coordinate.pad, hash.pad.
        data);
     hash.data.len = sp_unsigned_bin_size(backup->
        encrypted_coordinate.data);
     hash.data.data = (uint8_t*)malloc(hash.data.len);
     sp_to_unsigned_bin(backup->encrypted_coordinate.data, hash.data
        .data);
     hash.mac.len = sp_unsigned_bin_size(backup->
        encrypted_coordinate.mac);
     hash.mac.data = (uint8_t*)malloc(hash.mac.len);
     sp_to_unsigned_bin(backup->encrypted_coordinate.mac, hash.mac.
        data);
     proto.encrypted_coordinate = &hash;

     *len = election_partial_key_pair_backup_proto__get_packed_size
        (&proto);
     uint8_t* buffer = (uint8_t *)calloc(*len, sizeof(char));
     election_partial_key_pair_backup_proto__pack(&proto, buffer);
     return buffer;
}
```

A.3.2. Deserialization

```
int deserialize_ciphertext_tally(uint8_t *buffer, unsigned len,
    CiphertextTally* ciphertally) {
     CiphertextTallyProto* tally = ciphertext_tally_proto__unpack(
        NULL, len, buffer);
     if (tally == NULL) {
          fprintf(stderr, "Error unpacking CiphertextTallySelections\
             n");
          return -1;
     }
```

```
    ciphertally->object_id = strdup(tally->object_id);
    ciphertally->base_hash = NULL;
    ciphertally->base_hash = (sp_int*)XMALLOC(MP_INT_SIZEOF(
        MP_BITS_CNT(256)), NULL, DYNAMIC_TYPE_BIGINT);
    sp_read_unsigned_bin(ciphertally->base_hash, tally->base_hash.
        data, tally->base_hash.len);

    ciphertally->num_contest = tally->num_contest;
    ciphertally->contests = (CiphertextTallyContest*)malloc(sizeof(
        CiphertextTallyContest) * ciphertally->num_contest);
    for(int i = 0; i < ciphertally->num_contest; i++) {
        ciphertally->contests[i].object_id = strdup(tally->contests
            [i]->object_id);
        ciphertally->contests[i].sequence_order = tally->contests[i
            ]->sequence_order;
        ciphertally->contests[i].description_hash = NULL;
        ciphertally->contests[i].description_hash = (sp_int*)
            XMALLOC(MP_INT_SIZEOF(MP_BITS_CNT(256)), NULL,
            DYNAMIC_TYPE_BIGINT);
        sp_read_unsigned_bin(ciphertally->contests[i].
            description_hash, tally->contests[i]->description_hash.
            data, tally->contests[i]->description_hash.len);
        ciphertally->contests[i].num_selections = tally->contests[i
            ]->num_selections;

        ciphertally->contests[i].selections = (
            CiphertextTallySelection*)malloc(sizeof(
            CiphertextTallySelection) * ciphertally->contests[i].
            num_selections);
        for(int j = 0; j < ciphertally->contests[i].num_selections;
            j++) {
            ciphertally->contests[i].selections[j].object_id =
                strdup(tally->contests[i]->selections[j]->object_id)
                ;
            ciphertally->contests[i].selections[j].ciphertext_pad =
                NULL;
            ciphertally->contests[i].selections[j].ciphertext_pad =
                (sp_int*)XMALLOC(MP_INT_SIZEOF(MP_BITS_CNT(3072)),
                NULL, DYNAMIC_TYPE_BIGINT);
            sp_read_unsigned_bin(ciphertally->contests[i].
                selections[j].ciphertext_pad, tally->contests[i]->
                selections[j]->ciphertext_pad.data, tally->contests[
                i]->selections[j]->ciphertext_pad.len);
            ciphertally->contests[i].selections[j].ciphertext_data
                = NULL;
            ciphertally->contests[i].selections[j].ciphertext_data
                = (sp_int*)XMALLOC(MP_INT_SIZEOF(MP_BITS_CNT(3072)),
                NULL, DYNAMIC_TYPE_BIGINT);
            sp_read_unsigned_bin(ciphertally->contests[i].
                selections[j].ciphertext_data, tally->contests[i]->
                selections[j]->ciphertext_data.data, tally->contests
```

```
                [i]->selections[j]->ciphertext_data.len);
        }

    }


    ciphertext_tally_proto__free_unpacked(tally, NULL);
    return 0;
}
```

A.3.3. Proto file

```
syntax = "proto2";

message SchnorrProofProto {
    required bytes pubkey = 1;
    required bytes commitment = 2;
    required bytes challenge = 3;
    required bytes response = 4;
}

message CoefficientProto {
    required bytes value = 1;
    required bytes commitment = 2;
    required SchnorrProofProto proof = 3;
}

message ElectionPolynomialProto {
    required int32 num_coefficients = 1;
    repeated CoefficientProto coefficients = 2;
}

message ElectionKeyPairProto {
    required bytes guardian_id = 1; // fixed length of 6 bytes
    required bytes public_key = 2;
    required bytes private_key = 3;
    required ElectionPolynomialProto polynomial = 4;
}

message HashedElGamalCiphertextProto {
    required bytes pad = 1;
    required bytes data = 2;
    required bytes mac = 3;
}

message ElectionPartialKeyPairBackupProto {
    required bytes sender = 1; // fixed length of 6 bytes
    required bytes receiver = 2; // fixed length of 6 bytes
    required HashedElGamalCiphertextProto encrypted_coordinate = 3;
}
```

```
message ElectionPartialKeyVerificationProto {
    required bytes sender = 1; // fixed length of 6 bytes
    required bytes receiver = 2; // fixed length of 6 bytes
    required bytes verifier = 3; // fixed length of 6 bytes
    required bool verified = 4;
}
```

```
syntax = "proto2";


message PlaintextBallotSelectionProto {
        required bool vote = 1;
        required bool is_placeholder_selection = 2;
}


message PlaintextBallotContestProto {
        required int32 num_selections = 1;
        repeated PlaintextBallotSelectionProto ballot_selections =
           2;
}

message PlaintextBallotProto {
        required string style_id = 1;
        required int32 num_contests = 2;
        repeated PlaintextBallotContestProto contests = 3;
}


message CiphertextBallotProto {
        required string style_id = 1;
        required bytes code_seed = 2;
        required bytes code = 3;
        required bytes crypto_hash = 4;
}
```

```
syntax = "proto2";


message CiphertextTallySelectionProto {
        required string object_id = 1;
        required bytes ciphertext_pad = 2;
        required bytes ciphertext_data = 3;
}

message CiphertextTallyContestProto {
        required string object_id = 1;
        required int32 sequence_order = 2;
        required bytes description_hash = 3;
        required int32 num_selections = 4;
        repeated CiphertextTallySelectionProto selections = 5;
}
```

```
message CiphertextTallyProto {
        required string object_id = 1;
        required bytes base_hash = 2;
        required int32 num_contest = 3;
        repeated CiphertextTallyContestProto contests = 4;
}


message CiphertextDecryptionSelectionProto {
        required string object_id = 1;
        required bytes guardian_id  = 2;
        required bytes decryption = 3;
        required bytes proof_pad = 4;
        required bytes proof_data = 5;
        required bytes proof_challenge = 6;
        required bytes proof_response = 7;
}

message CiphertextDecryptionContestProto {
        required string object_id = 1;
        required bytes guardian_id = 2;
        required bytes description_hash = 3;
        required int32 num_selections = 4;
        repeated CiphertextDecryptionSelectionProto selections = 5;
}

message DecryptionShareProto {
        required string object_id = 1;
        required bytes guardian_id = 2;
        required bytes public_key = 3;
        required int32 num_contests = 4;
        repeated CiphertextDecryptionContestProto contests = 5;
}
```

A.3.4. Generated Code

```
/* Generated by the protocol buffer compiler.  DO NOT EDIT! */
/* Generated from: buff.proto */

/* Do not generate deprecated warnings for self */
#ifndef PROTOBUF_C__NO_DEPRECATED
#define PROTOBUF_C__NO_DEPRECATED
#endif

#include "buff.pb-c.h"
void   schnorr_proof_proto__init
                     (SchnorrProofProto         *message)
{
  static const SchnorrProofProto init_value =
     SCHNORR_PROOF_PROTO__INIT;
  *message = init_value;
```

```
}
size_t schnorr_proof_proto__get_packed_size
                     (const SchnorrProofProto *message)
{
  assert(message->base.descriptor == &
     schnorr_proof_proto__descriptor);
  return protobuf_c_message_get_packed_size ((const
     ProtobufCMessage*)(message));
}
size_t schnorr_proof_proto__pack
                     (const SchnorrProofProto *message,
                      uint8_t       *out)
{
  assert(message->base.descriptor == &
     schnorr_proof_proto__descriptor);
  return protobuf_c_message_pack ((const ProtobufCMessage*)message,
      out);
}
size_t schnorr_proof_proto__pack_to_buffer
                     (const SchnorrProofProto *message,
                      ProtobufCBuffer *buffer)
{
  assert(message->base.descriptor == &
     schnorr_proof_proto__descriptor);
  return protobuf_c_message_pack_to_buffer ((const ProtobufCMessage
     *)message, buffer);
}
SchnorrProofProto *
       schnorr_proof_proto__unpack
                     (ProtobufCAllocator  *allocator,
                      size_t               len,
                      const uint8_t       *data)
{
  return (SchnorrProofProto *)
     protobuf_c_message_unpack (&schnorr_proof_proto__descriptor,
                                allocator, len, data);
}
void   schnorr_proof_proto__free_unpacked
                     (SchnorrProofProto *message,
                      ProtobufCAllocator *allocator)
{
  if(!message)
    return;
  assert(message->base.descriptor == &
     schnorr_proof_proto__descriptor);
  protobuf_c_message_free_unpacked ((ProtobufCMessage*)message,
     allocator);
}
```

```
# -*- coding: utf-8 -*-
# Generated by the protocol buffer compiler.  DO NOT EDIT!
# source: ballot.proto
"""Generated protocol buffer code."""
```

```
from google.protobuf.internal import builder as _builder
from google.protobuf import descriptor as _descriptor
from google.protobuf import descriptor_pool as _descriptor_pool
from google.protobuf import symbol_database as _symbol_database
# @@protoc_insertion_point(imports)

_sym_db = _symbol_database.Default()



DESCRIPTOR = _descriptor_pool.Default().AddSerializedFile(b'\n\x0c\
    x62\x61llot.proto\"0\n\x1dPlaintextBallotSelectionProto\x12\x0c\
    n\x04vote\x18\x01 \x02(\x08\x12 \n\x18is_placeholder_selection\
    x18\x02 \x02(\x08\"p\n\x1bPlaintextBallotContestProto\x12\x16\n\
    x0enum_selections\x18\x01 \x02(\x05\x12\x39\n\x11\x62\
    x61llot_selections\x18\x02 \x03(\x0b\x32\x1e.
    PlaintextBallotSelectionProto\"n\n\x14PlaintextBallotProto\x12\
    x10\n\x08style_id\x18\x01 \x02(\t\x12\x14\n\x0cnum_contests\x18\
    x02 \x02(\x05\x12.\n\x08\x63ontests\x18\x03 \x03(\x0b\x32\x1c.
    PlaintextBallotContestProto\"_\n\x15\x43iphertextBallotProto\x12
    \x10\n\x08style_id\x18\x01 \x02(\t\x12\x11\n\tcode_seed\x18\x02
    \x02(\x0c\x12\x0c\n\x04\x63ode\x18\x03 \x02(\x0c\x12\x13\n\x0b\
    x63rypto_hash\x18\x04 \x02(\x0c')

_builder.BuildMessageAndEnumDescriptors(DESCRIPTOR, globals())
_builder.BuildTopDescriptorsAndMessages(DESCRIPTOR, 'ballot_pb2',
    globals())
if _descriptor._USE_C_DESCRIPTORS == False:

  DESCRIPTOR._options = None
  _PLAINTEXTBALLOTSELECTIONPROTO._serialized_start=16
  _PLAINTEXTBALLOTSELECTIONPROTO._serialized_end=95
  _PLAINTEXTBALLOTCONTESTPROTO._serialized_start=97
  _PLAINTEXTBALLOTCONTESTPROTO._serialized_end=209
  _PLAINTEXTBALLOTPROTO._serialized_start=211
  _PLAINTEXTBALLOTPROTO._serialized_end=321
  _CIPHERTEXTBALLOTPROTO._serialized_start=323
  _CIPHERTEXTBALLOTPROTO._serialized_end=418
# @@protoc_insertion_point(module_scope)
```