Aionda Mail Security Whitepaper

Zero-Knowledge · Post-Quantum · Made in Germany

Version 1.2 — April 2026

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PUBLIC DOCUMENT

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1. Aionda Mail Security Whitepaper

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1.2 1. Executive Summary

Aionda Mail is a zero-knowledge, post-quantum encrypted email service operated by Aionda GmbH in Stuttgart, Germany. The service combines disposable email addresses (DEAs) with a fully encrypted mailbox — a combination not offered by any other provider.

Core security properties:

- **Zero-Knowledge Architecture:** All encryption and decryption happens exclusively in the user's browser. The server never has access to plaintext email content in the secure mailbox, passwords, or encryption keys.
- **Post-Quantum Security:** Hybrid Key Encapsulation Mechanism (X25519 + ML-KEM-1024) protects all data against both classical and quantum computer attacks.
- **Zero-Knowledge Authentication:** OPAQUE protocol (RFC 9807) ensures passwords are never transmitted to or stored on the server — not even as hashes.
- **Shamir Secret Sharing (2-of-3):** The vault master key is split into three shares protected

by password, passkey, and recovery key. Any two shares reconstruct the master key.

- **Perfect Forward Secrecy:** Every API request uses a unique, one-time cryptographic keypair. Compromising one request does not affect any other.
- **MITM Protection (Guardian):** The browser extension independently verifies all server responses via Ed25519 signatures and detects man-in-the-middle attacks through TLS certificate verification — even against corporate proxies and compromised CDNs.
- **GoBD-Compliant Email Archive:** Enterprise accounts benefit from a tamper-evident hash chain (SHA3-256 blockchain) with end-to-end encrypted content (Hybrid KEM), complete audit trail, legal hold, and configurable retention — compliant with German GoBD regulations.
- **No Password Recovery:** If the password and all recovery methods are lost, the data is irrecoverable. This is by design — it proves the server cannot access user data.

Jurisdiction: German law (DSGVO/GDPR), no data sharing with foreign intelligence agencies.

1.3 2. Threat Model

1.3.1 2.1 What Aionda Mail Protects Against

Threat	Protection
Server compromise (database leak, insider access)	All email content encrypted with keys the server never possesses
Network eavesdropping (ISP, Wi-Fi, CDN)	End-to-end encrypted API transport via Hybrid KEM
CloudFlare inspection	API requests are encrypted before leaving the browser; CloudFlare sees only ciphertext. Guardian extension detects response tampering via Ed25519 signatures
Corporate MITM proxies (ZScaler, Fortinet, etc.)	Guardian extension detects proxy certificates via issuer blocklist (Firefox)
Quantum computer attacks ("harvest now, decrypt later")	ML-KEM-1024 (NIST FIPS 203) provides post-quantum resistance
Password database theft	OPAQUE stores only cryptographic records, not password hashes
Offline brute-force attacks on passwords	OPAQUE prevents offline attacks; server-side rate limiting prevents online attacks
Email size analysis	Bucket padding obscures actual email sizes
Compression side-channels (CRIME/BREACH)	Bucket padding applied after compression
User enumeration	Deterministic fake responses for non-existent accounts

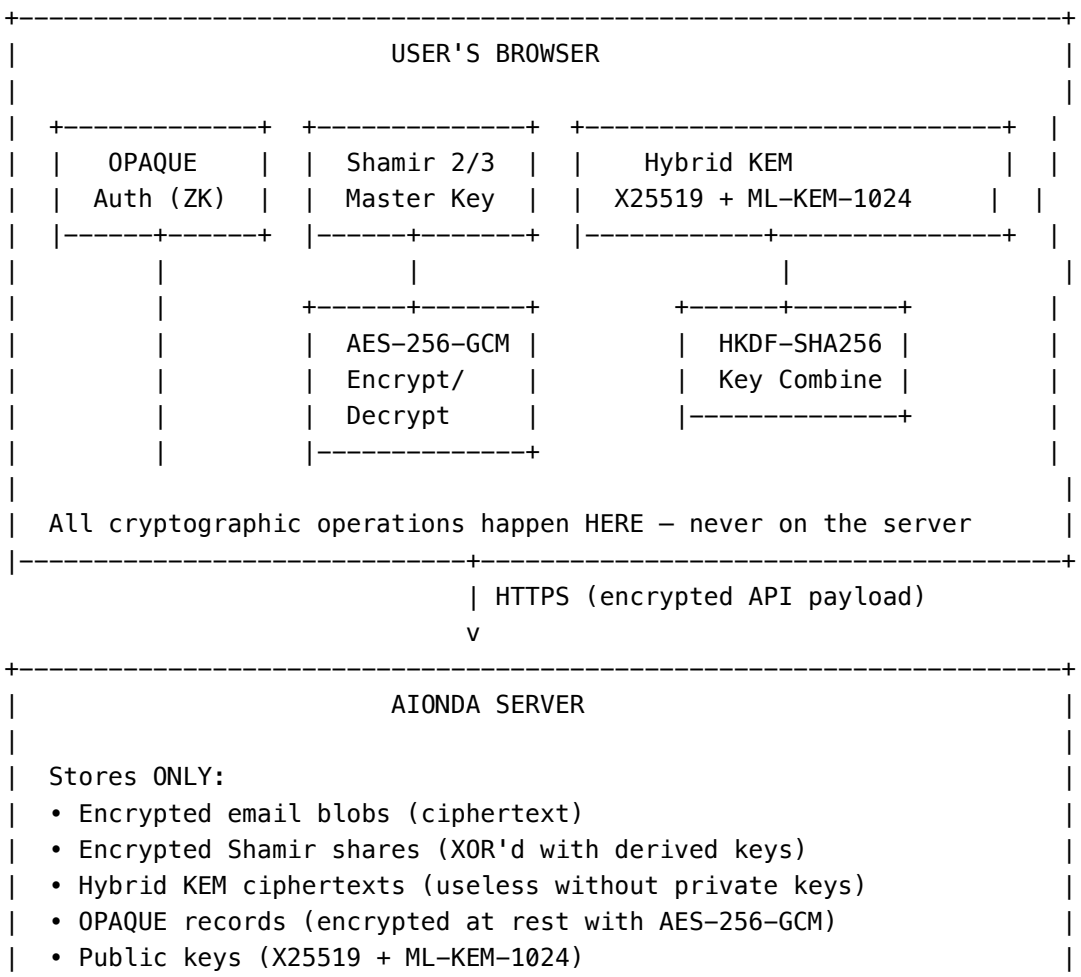
1.3.2 2.2 What Aionda Mail Does NOT Protect Against

Limitation	Explanation
Compromised device	If malware controls the browser, it can read decrypted content
Metadata to external recipients	Emails to Gmail/Outlook travel unencrypted after leaving our servers (unless PGP is used)
Email metadata on our servers	Timestamps, IP addresses, and encrypted email sizes are visible to the server
Web delivery trust	The browser downloads JavaScript from our servers on each visit (see Section 17 for mitigations)
Rubber-hose cryptanalysis	No cryptographic system protects against physical coercion

1.3.3 2.3 Design Principle

Aionda Mail follows the **"honest server" model**: the system is designed so that even a fully compromised server — or a malicious operator — cannot decrypt user data. Security does not depend on trusting us. It depends on mathematics.

1.4 3. Architecture Overview



```
|                                                                    |
|  CANNOT access: passwords, master keys, email content, private keys  |
|--------------------------------------------------------------------+
```

1.4.1 3.1 Component Overview

Component	Purpose	Location
OPAQUE (RFC 9807)	Zero-knowledge password authentication	Client + Server
Shamir Secret Sharing	Vault master key protection (2-of-3 threshold)	Client only
Hybrid KEM (X25519 + ML-KEM-1024)	Post-quantum key encapsulation for emails	Client + Server
AES-256-GCM	Authenticated symmetric encryption	Client + Server
HKDF-SHA256	Key derivation from hybrid shared secrets	Client + Server
BIP39	Recovery key encoding (24-word mnemonic)	Client only
WebAuthn PRF	Passkey-based vault unlock	Client only
Bucket Padding	Side-channel protection	Client + Server

1.5 4. Zero-Knowledge Authentication (OPAQUE)

1.5.1 4.1 Why Not Password Hashing?

Traditional services store password hashes (bcrypt, Argon2). While better than plaintext, this approach has fundamental weaknesses:

- The server sees the password during login (even if only briefly in RAM)
- Password hashes can be brute-forced offline if the database is stolen
- The server could be modified to log passwords

OPAQUE eliminates all three problems. The password never leaves the browser — not as plaintext, not as a hash, not in any form.

1.5.2 4.2 How OPAQUE Works

OPAQUE (RFC 9807) is an Asymmetric Password-Authenticated Key Exchange (aPAKE) protocol. It uses a cryptographic challenge-response mechanism where the server can verify the user knows the correct password without ever learning what that password is.

Registration (one-time):

```
Browser                                  Server
--------                                 ------
1. Generate OPAQUE registration     →
   request from password
```

```
                                        2. Create OPAQUE registration
                                           response (blind evaluation)
                                    ←
3. Finalize registration            →   4. Store encrypted OPAQUE
   (export_key available)                   record (AES-256-GCM at rest)
```

Login (every session):

```
Browser                                 Server
--------                                ------
1. Generate login request (KE1)     →   2. Look up encrypted OPAQUE record
   from password                            Decrypt with server key
                                            Generate response (KE2)
                                    ←
3. Verify server response
   Compute session key + KE3        →   4. Verify KE3 (cryptographic proof)
   Password verified locally!               If valid: session authenticated
                                            If invalid: reject (max 3 attempts)
```

Key properties:

- Password is verified **client-side** in step 3 — the server never sees it
- The server stores an **OPAQUE record**, which is not a password hash and cannot be brute-forced offline
- OPAQUE records are additionally **encrypted at rest** with AES-256-GCM using a server-side key
- **User enumeration protection**: Non-existent accounts receive deterministic fake responses with identical timing
- **Rate limiting**: Maximum 3 authentication attempts per session, 120-second session timeout

1.5.3 4.3 Implementation

- **Library:** `@serenity-kit/opaque` (WASM-based, production-grade)
- **Server component:** Dedicated microservice for OPAQUE cryptographic operations
- **Base64 format:** base64url (URL-safe, no padding) for protocol compatibility
- **Audit logging:** All authentication events logged with timestamps and IP addresses

1.5.4 4.4 SRP Migration

Legacy accounts using SRP-6a are automatically migrated to OPAQUE upon next login. After migration, the SRP verifier is permanently deleted. Migration is one-way — accounts cannot revert to SRP.

1.6 5. Vault Master Key & Shamir Secret Sharing

1.6.1 5.1 Master Key Generation

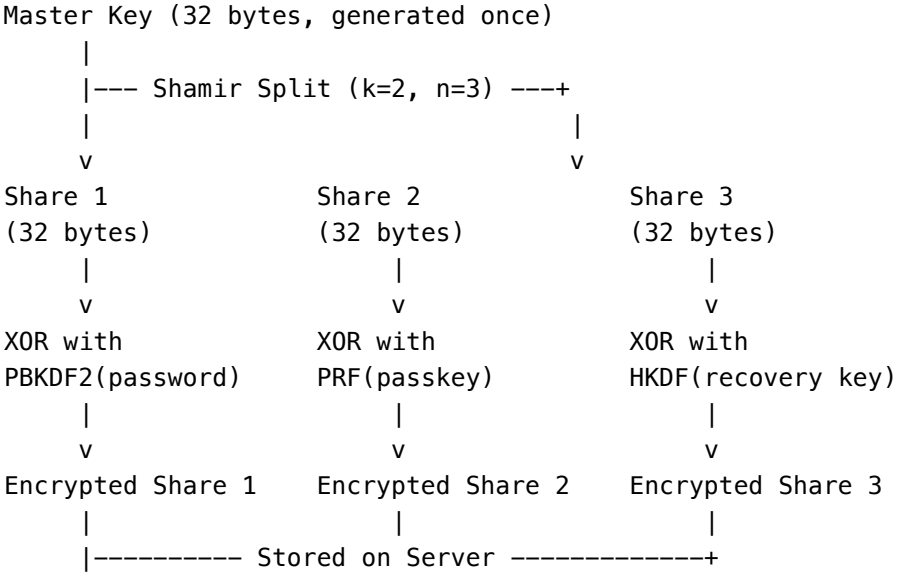
When a user activates the encrypted mailbox, a **256-bit (32-byte) master key** is generated using the browser's cryptographically secure random number generator (`crypto.getRandomValues`).

This master key is the root of all encryption. It never leaves the browser in plaintext. It is never

stored anywhere — not in the browser, not on the server, not in any form.

1.6.2 5.2 Shamir Secret Sharing (2-of-3)

The master key is split into three shares using **Shamir's Secret Sharing** scheme over the Galois Field GF(2^8) with the AES irreducible polynomial (x^8 + x^4 + x^3 + x + 1).



Threshold property: Any 2 of the 3 shares are sufficient to reconstruct the master key via Lagrange interpolation. The server stores only the encrypted shares — and cannot decrypt any of them.

1.6.3 5.3 Share Protection

Each share is XOR'd with a key derived from a different authentication factor:

Share	Protected By	Key Derivation
Share 1	Password	PBKDF2-SHA256, 600,000 iterations, 32-byte random salt
Share 2	Passkey (FIDO2)	WebAuthn PRF extension, hardware-bound
Share 3	Recovery Key	HKDF-SHA3-256 with account-bound salt

Reconstruction scenarios:

- **Normal login:** Password (Share 1) + Passkey (Share 2) → Master Key
- **Lost passkey:** Password (Share 1) + Recovery Key (Share 3) → Master Key
- **Password change:** Passkey (Share 2) + Recovery Key (Share 3) → Master Key

1.6.4 5.4 Session Storage Protection

Even within a browser session, the master key is never stored in plaintext:

1. An ephemeral AES-256 key is generated
2. The master key is encrypted with this ephemeral key

3. Only the encrypted blob is placed in `sessionStorage`
4. The ephemeral key exists only in JavaScript memory (garbage-collected on tab close)

1.7 6. Post-Quantum Hybrid KEM

1.7.1 6.1 Why Post-Quantum?

Quantum computers running Shor's algorithm could break classical public-key cryptography (RSA, ECDH, X25519) in polynomial time. While large-scale quantum computers do not yet exist, the threat of **"harvest now, decrypt later"** attacks is real: adversaries could store encrypted data today and decrypt it when quantum computers become available.

1.7.2 6.2 Hybrid Approach

Aionda Mail uses a **hybrid Key Encapsulation Mechanism** combining:

- **X25519** (Curve25519 ECDH) — proven classical security, 128-bit security level
- **ML-KEM-1024** (NIST FIPS 203, formerly Kyber-1024) — post-quantum security, NIST Security Level 5

The hybrid approach provides **defense-in-depth**: the combined key is secure as long as **at least one** of the two algorithms remains unbroken.

1.7.3 6.3 Encapsulation Process

```
Sender (encrypting an email):

1. Generate ephemeral X25519 keypair
2. X25519 key agreement with recipient's public key
   → x25519SharedSecret (32 bytes)

3. ML-KEM-1024 encapsulation with recipient's public key
   → mlKemSharedSecret (32 bytes) + mlKemCiphertext (1568 bytes)

4. Combine secrets:
   combinedSecret = x25519SharedSecret || mlKemSharedSecret  (64 bytes)

5. Derive final key:
   sharedSecret = HKDF-SHA256(
       ikm = combinedSecret,
       salt = nil,
       info = "trashmail-hybrid-kem-v1",
       length = 32
   )

6. Use sharedSecret to wrap the email's ephemeral AES-256 key
```

1.7.4 6.4 Decapsulation Process

```
Recipient (decrypting an email):

1. X25519 key agreement:
```

```
   x25519Shared = X25519(recipientPrivateKey, ephemeralPublicKey)

2. ML-KEM-1024 decapsulation:
   mlKemShared = ML-KEM-1024.Decapsulate(mlKemCiphertext, recipientPrivateKey)

3. Combine and derive (identical to sender):
   sharedSecret = HKDF-SHA256(x25519Shared || mlKemShared, "trashmail-hybrid-kem-v1")

4. Unwrap email's ephemeral AES-256 key using sharedSecret
5. Decrypt email content with ephemeral key
```

1.7.5 6.5 Key Sizes

Parameter	Size	Standard
X25519 public key	32 bytes	RFC 7748
X25519 private key	32 bytes	RFC 7748
ML-KEM-1024 public key	1,568 bytes	NIST FIPS 203
ML-KEM-1024 private key	3,168 bytes	NIST FIPS 203
ML-KEM-1024 ciphertext	1,568 bytes	NIST FIPS 203
Combined shared secret	32 bytes	HKDF-SHA256 output

1.7.6 6.6 Library

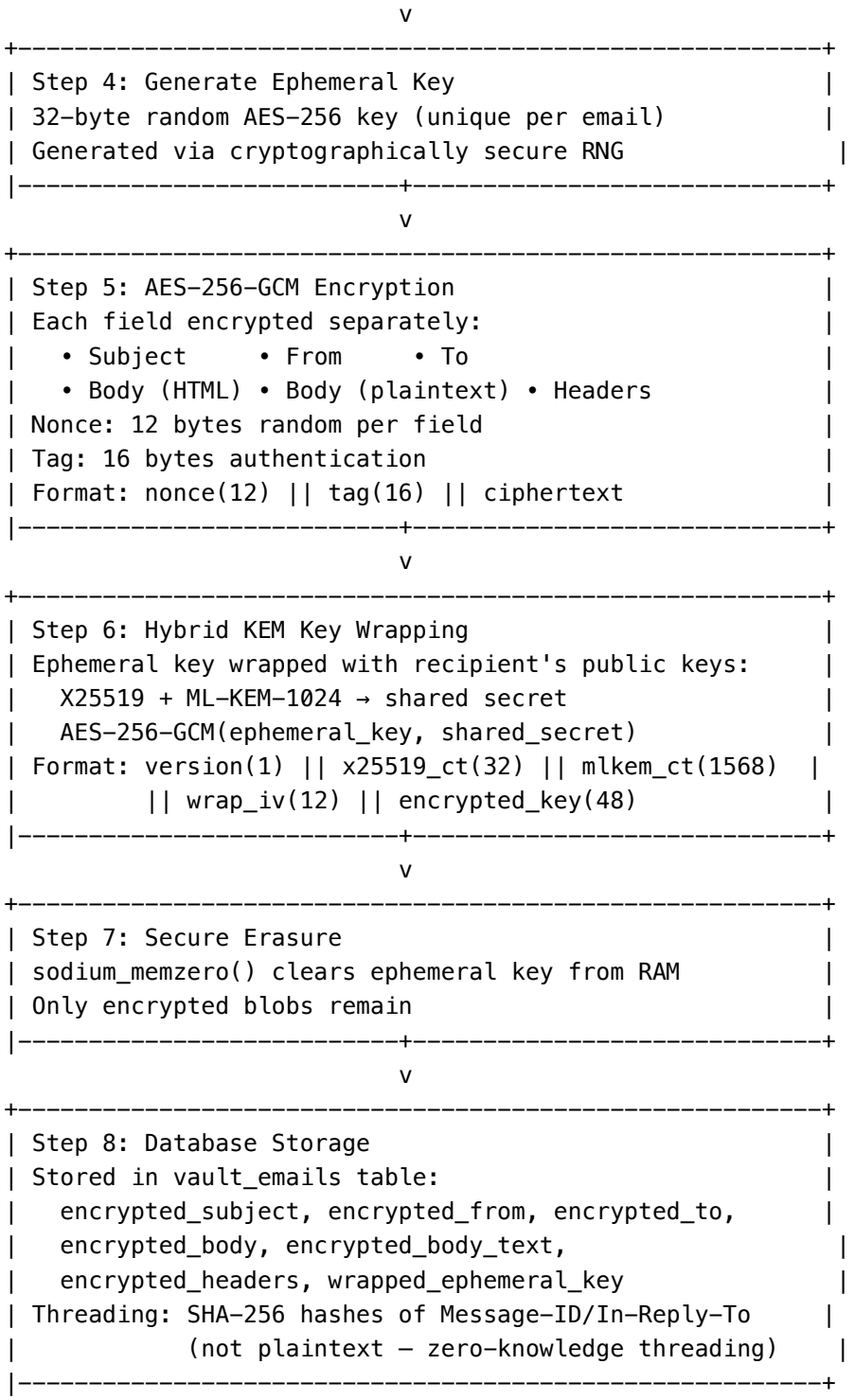
- **ML-KEM-1024:** `@noble/post-quantum` (audited, pure JavaScript implementation)
- **X25519:** WebCrypto API (`crypto.subtle.deriveBits`)
- **HKDF:** `@noble/hashes` (RFC 5869 compliant)

1.8 7. Email Encryption Pipeline

1.8.1 7.1 Incoming Email (SMTP □ Encrypted Storage)

When an email arrives at Aionda Mail's SMTP server:

```
+-----------------------------------------------------------+
| Step 1: SMTP Reception                                    |
| Mail server receives email → passes to SMTP handler       |
|-------------------------+---------------------------------+
                          v
+-----------------------------------------------------------+
| Step 2: Compression (optional)                            |
| gzip level 6 for text content                             |
| Skipped for: JPEG, PNG, MP4, ZIP, PDF, DOCX, etc.         |
|-------------------------+---------------------------------+
                          v
+-----------------------------------------------------------+
| Step 3: Bucket Padding                                    |
| Pad to fixed-size bucket (256B, 512B, 1KB, ..., 16MB)     |
| Format: 0xDEAD || length(4B) || data || random padding    |
|-------------------------+---------------------------------+
```



1.8.2 7.2 Reading Email (Browser Decryption)

The reverse process happens entirely in the browser:

1. Fetch encrypted email from server via encrypted API
2. Parse wrapped ephemeral key (extract X25519 ciphertext + ML-KEM ciphertext)
3. **Hybrid KEM decapsulation** using vault private keys shared secret
4. Unwrap ephemeral AES-256 key

5. **AES-256-GCM decryption** of each field (subject, from, to, body, headers)
6. Reorder bytes: server format (nonce || tag || ct) □ WebCrypto format (nonce || ct || tag)
7. Remove bucket padding (detect 0xDEAD magic bytes)
8. Decompress if gzip (detect 0x1F8B magic bytes)
9. UTF-8 decode to plaintext

1.8.3 7.3 Sending Email

When composing and sending an email:

1. Client encrypts email content with a challenge-response protocol
2. Server receives encrypted payload, decrypts ephemerally (in-memory only), sends via SMTP
3. Server returns generated MIME headers to client (encrypted)
4. Client encrypts a copy with vault master key and stores in Sent folder
5. Ephemeral server-side plaintext is immediately discarded — never written to disk

1.8.4 7.4 Attachments

Each attachment is encrypted independently:

- Separate ephemeral AES-256 key per attachment
- Separate Hybrid KEM key wrapping per attachment
- Filename and MIME type encrypted separately
- No compression for already-compressed formats (JPEG, ZIP, PDF, etc.)

1.8.5 7.5 Email Threading (Zero-Knowledge)

Email threading (grouping related emails) uses only **SHA-256 hashes** of Message-ID and In-Reply-To headers. The server never sees the actual Message-ID strings — it can group emails by hash equality without knowing the content.

1.9 8. Encrypted API Transport Layer

1.9.1 8.1 Problem

Even with HTTPS, certain intermediaries can inspect traffic:

- **CloudFlare** (CDN/DDoS protection) terminates TLS and can see plaintext requests
- **Corporate proxies** may perform TLS inspection
- **API parameters** (like `?cmd=read_email&id=123`) leak metadata

1.9.2 8.2 Solution: End-to-End Encrypted API

All API communication is additionally encrypted end-to-end between the browser and the application server, inside the HTTPS tunnel:

```
Browser                                    Server
────────                                   ──────

Phase 1: Key Exchange (once per session)
──────────────────────────────────────
```

```
GET /get_encryption_keys          →         Return 20 pre-generated
                                            Hybrid KEM keypairs
                                  ←         {uuid, x25519_pub, mlkem_pub}

Phase 2: Encrypted Request (every API call)
-------------------------------------
1. Pick random keypair from cache
2. Hybrid KEM encapsulate → shared secret
3. gzip compress request payload
4. Bucket-pad compressed data
5. AES-256-GCM encrypt with shared secret
6. Generate ephemeral response keypair
7. POST /e {                      →         8.  Validate key ownership
     encrypted_payload,                     9.  Hybrid KEM decapsulate
     key_uuid,                              10. AES-256-GCM decrypt
     x25519_ciphertext,                     11. Decompress
     mlkem_ciphertext,                      12. Route to API controller
     response_x25519_pub,                   13. Execute business logic
     response_mlkem_pub                     14. Encrypt response with
   }                                            client's response keys
                                  ←         15. Return encrypted response
16. Hybrid KEM decapsulate response
17. AES-256-GCM decrypt
18. Decompress → plaintext response
```

1.9.3 8.3 Key Properties

- **One-time use:** Each API keypair is used exactly once, then permanently invalidated
- **Perfect Forward Secrecy:** Compromising one request key does not affect any other request
- **Session-bound:** Keys are claimed by a specific session and cannot be reused by another
- **Key pool:** Server maintains approximately 100,000 pre-generated keypairs
- **Auto-refetch:** Client automatically requests new keys when cache drops below 10
- **Key TTL:** Claimed keys expire after 24 hours
- **Bidirectional:** Both request AND response are encrypted — the server never returns plaintext

1.9.4 8.4 What CloudFlare Sees

With this architecture, CloudFlare (or any TLS-terminating proxy) sees only:

- `POST /e` — a single, opaque endpoint
- A binary blob of encrypted data
- No API command names, no parameters, no email IDs, no user data

---

1.10 9. Folder Sharing Cryptography

1.10.1 9.1 Sharing Model

Users can share encrypted folders with other Aionda Mail users. The sharing mechanism uses the Hybrid KEM to encrypt a folder-specific key for each recipient.

1.10.2 9.2 Sharing Flow

```
Folder Owner                                          Recipient
------------                                          ---------

1. Derive folder key from master key:
   folderKey = HKDF-SHA256(masterKey, folderUuid)

2. Fetch recipient's public keys:
   recipient.x25519_pub (32 bytes)
   recipient.mlkem_pub (1568 bytes)

3. Hybrid KEM encapsulate:
   hybridEncapsulate(recipient.x25519_pub, recipient.mlkem_pub)
   → {x25519Ciphertext, mlKemCiphertext, sharedSecret}

4. Encrypt folder key:
   wrappedKey = AES-256-GCM(folderKey, sharedSecret, nonce)

5. Store on server:
   {x25519_ct, mlkem_ct, nonce, wrappedKey, permissions}

                                                      6. Fetch sharing record from server

                                                      7. Hybrid KEM decapsulate:
                                                         hybridDecapsulate(x25519_ct, mlkem_ct,
                                                           own_x25519_priv, own_mlkem_priv)
                                                         → sharedSecret

                                                      8. Decrypt folder key:
                                                         folderKey = AES-GCM-decrypt(
                                                           wrappedKey, sharedSecret, nonce)

                                                      9. Decrypt emails in folder using folderKe
```

1.10.3 9.3 Permission Model

Permission	Capability
`readonly`	Read folder emails (decrypt only)
`einliefern`	Submit new emails into folder
`bearbeiten`	Edit folder contents
`antworten`	Reply to emails within folder
`vollzugriff`	Full access including ownership transfer

1.10.4 9.4 Cross-Vault Copy (Re-Wrapping)

When a recipient copies an email from a shared folder to their own vault, the email key must be **re-wrapped** for their own Hybrid KEM keypair. This is performed entirely client-side:

1. Decrypt shared folder key using recipient's private keys
2. Decrypt email's ephemeral key using folder key
3. Re-encapsulate ephemeral key with recipient's own public keys
4. Store re-wrapped copy in recipient's vault

The server facilitates the transfer but never sees any plaintext key material.

1.11 10. Vault Drive — Encrypted Document Storage

Vault Drive is the zero-knowledge document storage of Aionda Mail. Unlike emails, which use per-message ephemeral keys, Drive uses a **per-file-key architecture**: every document receives its own 32-byte AES-256-GCM key, generated client-side and wrapped with the master key.

1.11.1 10.1 Why per-file keys?

The per-file-key architecture offers three key advantages:

1. **Granular sharing:** Individual documents can be shared without exposing the master key. The server simply re-wraps the file key for the recipient — the content remains unchanged.
2. **Compromise isolation:** If a single file key is compromised (e.g. via a shared link), all other documents remain protected.
3. **Efficient sharing without re-encryption:** When sharing, the content does not need to be re-encrypted — all recipients read the same ciphertext with a re-wrapped key.

1.11.2 10.2 Upload flow

```
Client                                                  Server
------                                                  ------

1. Generate random file key:
   fileKey = randomBytes(32)

2. Encrypt content, name, MIME type:
   encContent = AES-256-GCM(content, fileKey, nonce1)
   encName    = AES-256-GCM(name,    fileKey, nonce2)
   encMime    = AES-256-GCM(mime,    fileKey, nonce3)

3. Wrap file key with master key:
   wrappedKey = AES-256-GCM(fileKey, masterKey, nonce4)

4. Send encrypted package:
   POST /e {
     encContent, encName, encMime,
     wrappedKey, wrappedKeyNonce
```

```
   }
                                                    5. Store in vault_files + vault_file_chunk
                                                       (pure ciphertexts, no key material)
```

1.11.3 10.3 Download flow

```
1. Fetch chunk + wrapped_key from server
2. Unwrap file key:
   fileKey = AES-256-GCM-decrypt(wrappedKey, masterKey, nonce)
3. Decrypt content, name, MIME:
   content = AES-256-GCM-decrypt(encContent, fileKey, nonce1)
```

Decryption happens inside a **Web Worker** that holds the master key only temporarily in memory. After the operation, the memory is overwritten.

1.11.4 10.4 Sharing — key rewrap only

The central advantage of per-file keys shows when sharing: the content is **not** re-encrypted. Only the 32-byte file key is re-wrapped using the recipient's hybrid KEM.

```
Owner                                               Recipient
-----                                               ---------

1. Unwrap file key:
   fileKey = AES-GCM-decrypt(wrappedKey, masterKey)

2. Fetch recipient's public keys:
   recipient.x25519_pub, recipient.mlkem_pub

3. Hybrid KEM encapsulation:
   hybridEncapsulate(recipient.x25519_pub,
                     recipient.mlkem_pub)
   → {x25519_ct, mlkem_ct, sharedSecret}

4. Wrap file key with sharedSecret:
   shareWrappedKey = AES-256-GCM(fileKey,
                                 sharedSecret, nonce)

5. Store share record:
   INSERT INTO vault_file_shares {
     file_uuid, recipient_account_id,
     x25519_ephemeral, mlkem_ciphertext,
     share_wrapped_key, permissions
   }
                                                    6. Fetch share record + chunk
                                                    7. Hybrid KEM decapsulation:
                                                       hybridDecapsulate(x25519_ct, mlkem_ct,
                                                         own_x25519_priv, own_mlkem_priv)
                                                       → sharedSecret
                                                    8. Unwrap file key:
                                                       fileKey = AES-GCM-decrypt(
                                                         shareWrappedKey, sharedSecret)
```

```
9. Decrypt SAME ciphertext:
   content = AES-GCM-decrypt(
     encContent, fileKey)
```

The owner does not need the recipient's master key — only the public hybrid KEM keys, which the server stores in plaintext.

1.11.5 10.5 Folder sharing (recursive)

When a folder is shared, the client processes all contained documents and subfolders recursively. Each file receives its own share record containing the respective document's file key, re-wrapped for the recipient. The folder itself has no folder key — the structure is linked via parent UUIDs.

Important: The KEM encapsulation step is performed **per operation**, not per file. All files in a batched share use the same `sharedSecret` — making the operation efficient without reducing security (each file still has its own file key).

1.11.6 10.6 Permission model

Permission	Can perform
Read	Download, preview, read metadata
Full access	+ rename, upload new version, move inside the shared folder, upload new documents
Not possible	Delete (owner only), move out of shared folder (owner only)

Permissions are stored in the `vault_file_shares` record and enforced server-side. Cryptography protects the content — access control protects the operations.

1.11.7 10.7 Rename, overwrite and metadata updates

For shared documents, rename and overwrite operations are performed directly on the `vault_files` record — not on individual share records. All recipients immediately see the new name or content, as they reference the same ciphertext.

On **overwrite** (new version), a **new file key** is generated, the old ciphertext is replaced, and all existing share records are re-wrapped client-side with the new key. The owner must load the public keys of all recipients for this operation.

1.11.8 10.8 Preview and in-memory decryption

Images, PDFs and other documents are decrypted **exclusively in memory** for preview. There is no disk cache with plaintext data. The client uses the **VaultDataLayer**, an encrypted IndexedDB cache that persistently stores ciphertexts and only decrypts them on demand.

Thumbnails are **never** generated server-side — the server never sees content. Thumbnails are generated client-side from the decrypted original and cached encrypted as well.

1.11.9 10.9 What the server sees

Visible to server	Not visible
Encrypted content (random bytes)	Plaintext content
Encrypted filename (random bytes)	Plaintext filename
Encrypted MIME type (random bytes)	File type (image, PDF, text…)
File size (padded to bucket boundaries)	Actual original size
Upload timestamp	File key, master key
Owner account ID	Contents of subfolders
Parent folder UUID (for structure)	Folder names (also encrypted)
Share records with KEM ciphertexts	Recipient master key, unwrapped file key

1.11.10 10.10 Quota enforcement

Quota enforcement happens server-side based on the **encrypted file size** (including bucket padding). The server does not know the actual plaintext size — the padding overhead is intentionally paid by the user to prevent size leakage.

Limits: - **Free:** 100 MB total storage, max. 10 MB per document - **Plus:** 1 GB total storage, max. 100 MB per document

1.11.11 10.11 External Sharing — public share links

Vault Drive documents can be shared with recipients who **do not have an Aionda Mail account** via public share links served from the isolated domain `mail.aionda.com`. The feature preserves zero-knowledge by treating each share as an **independent crypto envelope**, decoupled from the owner's vault master key.

Protection modes:

Mode	Trust factor	Use case
`link_only`	URL fragment (never sent to server)	Convenience — anyone with the link can access
`password`	Argon2id-derived key	Out-of-band password transfer (SMS, phone call)
`recipient_pubkey`	Hybrid KEM (X25519 + ML-KEM-1024)	Post-quantum secure when recipient has pre-registered public keys

10.11.1 Share creation (owner client)

```
1. fileKey := AES-GCM-decrypt(vault_files.wrapped_key, masterKey)
2. shareKey := randomBytes(32)                          // ephemeral, per share
3. wrappedFileKey := AES-GCM(fileKey, shareKey)         // new envelope
4. unlockVerifier := HMAC-SHA256(shareKey,
                     "unlock:" || shareUuid)            // proof-of-knowledge
5. If password protection:
     salt := randomBytes(16)
     pwKey := Argon2id(password, salt, t=3, m=64MB, p=1)
     wrappedShareKey := AES-GCM(shareKey, pwKey)
     → Link: https://mail.aionda.com/s/<shareUuid>
```

```
   Else (link_only):
     → Link: https://mail.aionda.com/s/<shareUuid>#<base64(shareKey)>
       (URL fragment — browsers never transmit fragments to the server)

6. Encrypted metadata (per-share, with shareKey):
     encFilename, encMime, encMessage  // all AES-GCM
7. POST /e  (encrypted API transport, see §8)
   → server stores share record — never sees plaintext
```

Link delivery is user-chosen, not routed through Aionda Mail. After creation, the owner decides which channel transports the link: copy-to-clipboard, QR code, a pre-filled `mailto:` draft opened in the user's own mail client, Signal, SMS, AirDrop, or any other out-of-band channel. Aionda Mail never sees, sends, or logs the outgoing delivery — the server only learns which share-UUIDs exist. This matters for two reasons: (a) the owner can select the most trusted channel available to them (a corporate compliance policy, a preferred messenger, a verified face-to-face QR scan), and (b) for `password`-protected shares it enables **channel separation** — link via channel A, password via channel B — so a single compromised channel never grants access on its own.

10.11.2 Share access (recipient, no account required) The recipient visits `https://mail.aionda.com/s/<s` The Share Page is a **separate bundle** from the Manager, with its own reproducible build, Subresource Integrity manifest, and a `/.well-known/integrity.json` endpoint for offline verification.

```
1. Share Page bootstrap (client generates ephemeral hybrid KEM keypair)
2. share_fetch_meta → { wrapped_file_key, salt?, encrypted_message, ... }
3. Unlock phase — produces a one-time unlock_token:
     password mode:    server verifies Argon2id derivation → unlock_token
     link_only mode:   client computes HMAC-SHA256(shareKey, "unlock:"||uuid)
                       server verifies against stored unlockVerifier
                       → unlock_token
4. fileKey := AES-GCM-decrypt(wrappedFileKey, shareKey)
5. share_download_chunk (per chunk, unlock_token required)
6. Client hashes plaintext, calls share_confirm_download
```

The `unlock_token` unifies the flow across all three protection modes and enables centralized rate-limiting and audit-logging — link-only access requires proof of knowledge of the fragment, so bots and crawlers without the fragment cannot issue downloads.

10.11.3 Enforced policies Every share must declare the following at creation time (all enforced server-side):

- **`expires_at`** — mandatory, default 7 days, maximum 90 days
- **`max_downloads`** — mandatory counter, default 10
- **Rate limiting** — Argon2 attempts on password shares are throttled per IP hash and per share
- **`revoked_at`** — the owner can revoke any share with a single click; future unlock attempts and downloads return a unified "share unavailable" response (same error as expired or exhausted — no enumeration oracle)

10.11.4 Tamper-evident audit chain All relevant access events are appended to the existing `enterprise_audit_log` hash chain (SHA3-256, see §16.2). The following action types are reserved for external sharing:

`EXT_SHARE_CREATED`, `EXT_SHARE_EMAIL_SENT`, `EXT_SHARE_VIEWED`, `EXT_SHARE_UNLOCKED`, `EXT_SHARE_PREVIEWED`, `EXT_SHARE_DOWNLOAD_STARTED`, `EXT_SHARE_DOWNLOAD_CONFIRMED`, `EXT_SHARE_INTEGRITY_BROKEN`, `EXT_SHARE_PASSWORD_FAIL`, `EXT_SHARE_REVOKED`, `EXT_SHARE_ROTATED`, `EXT_SHARE_EXPIRED`.

IP and user-agent hashes use a **daily rotating salt** (`vault_drive_external_share_daily_salts`, pruned after 30 days) — historical hashes become non-reversible after salt rotation for GDPR compliance, while short-term correlation remains available for the owner.

10.11.5 Key rotation (share rewrap) The owner can rotate a share at any time without re-uploading the content:

```
1. new_shareKey := randomBytes(32)
2. new_wrappedFileKey := AES-GCM(fileKey, new_shareKey)
3. INSERT new share row; old.linked_to_uuid := new.share_uuid
4. old.revoked_at := NOW()
```

Recipients using the old link receive “share unavailable”. The owner forwards the new link. All access events from both shares remain linked via `linked_to_uuid` in the audit chain.

10.11.6 What revocation does — and does not Revocation **stops future server-side delivery** of the share. It does **not** retroactively revoke share keys, file keys, or chunks already delivered. A recipient who has already downloaded the plaintext — or who captured the link fragment — can continue to use that material locally. For use cases with higher assurance requirements, combine: short `expires_at`, low `max_downloads`, password protection, and the Guardian browser extension for the recipient.

10.11.7 What the server sees

Visible to server	Not visible
`share_uuid`, `file_uuid`, `account_id` (owner)	Plaintext filename, MIME type, content, message
`wrapped_file_key`, `wrapped_share_key` (ciphertexts)	`share_key` (link-only: lives only in the URL fragment, client-side)
`unlock_verifier` (HMAC output, not reversible)	Password, Argon2-derived key
`protection_mode`, `expires_at`, `max_downloads`, `allow_preview`	Recipient identity (only salted IP/UA hash, pruned after 30 days)
`encrypted_filename`, `encrypted_mime`, `encrypted_message` (ciphertexts)	Their plaintexts
Plaintext `sender_display_name` (recipient sees it before unlock)	
Audit-chain entries for every access event	

1.12 11. Side-Channel Protections

1.12.1 11.1 Bucket Padding

Problem: Encrypted email sizes can leak information. An attacker observing ciphertext lengths could infer content (e.g., a 50-byte email is likely "OK, thanks" while a 500KB email contains attachments).

Solution: All data is padded to fixed-size "buckets" before encryption:

```
Bucket sizes: 256B, 512B, 1KB, 2KB, 4KB, 8KB, 16KB, 32KB,
              64KB, 128KB, 256KB, 512KB, 1MB, 2MB, 4MB, 8MB, 16MB

Format: [0xDEAD magic][4-byte length][actual data][random padding to bucket boundary]
```

Example: A 523-byte email is padded to 1,024 bytes. An observer sees only "1KB email" — not the actual 523-byte size.

1.12.2 11.2 Compression-Before-Encryption

Data is compressed with gzip (level 6) **before** encryption. This is the only correct order:

- Compression after encryption would fail (encrypted data has maximum entropy)
- The bucket padding after compression prevents CRIME/BREACH-style attacks that exploit compression ratios

1.12.3 11.3 Threading Privacy

Email threads use SHA-256 hashes of Message-ID headers instead of plaintext identifiers. The server can group related emails by hash equality without knowing the actual message identifiers.

1.13 12. Key Management & Lifecycle

1.13.1 12.1 Key Hierarchy

```
Vault Master Key (32 bytes, generated once per account)
   |
   |--- Vault Keypair (Hybrid KEM)
   |    |-- X25519 public key (32 bytes) — stored plaintext on server
   |    |-- X25519 private key (32 bytes) — encrypted with master key
   |    |-- ML-KEM-1024 public key (1568 bytes) — stored plaintext on server
   |    |-- ML-KEM-1024 private key (3168 bytes) — encrypted with master key
   |
   |--- Per-Email Ephemeral Keys (32 bytes each)
   |    |-- Wrapped with recipient's Hybrid KEM public keys
   |
   |--- Per-Attachment Ephemeral Keys (32 bytes each)
   |    |-- Wrapped independently per attachment
   |
   |--- Folder Keys (derived via HKDF per folder)
   |    |-- Shared via Hybrid KEM encapsulation per recipient
   |
```

```
   |--- Signature Encryption Key (derived from master key)
        |-- Encrypts email signature templates
```

1.13.2 12.2 Key Storage

Key	Storage Location	Protection
Master Key	Nowhere (reconstructed on-demand from Shamir shares)	Shamir 2-of-3
Vault private keys	Server (encrypted)	AES-256-GCM with master key
Vault public keys	Server (plaintext)	Not sensitive — public by definition
Email ephemeral keys	Server (wrapped)	Hybrid KEM encapsulation
OPAQUE records	Server (encrypted at rest)	AES-256-GCM with server key
Encrypted Shamir shares	Server	XOR with password/passkey/recovery derived keys
API transport keys	Server (pre-generated pool)	One-time use, 24h TTL

1.13.3 12.3 Key Fingerprints

Each vault keypair has a SHA-256 fingerprint stored on the server. This allows:

- Audit trail of key rotations
- Detection of unauthorized key changes
- Client-side verification of key integrity

1.14 13. Recovery Mechanism

1.14.1 13.1 Recovery Key (BIP39 Mnemonic)

During vault setup, the user is presented with a **24-word recovery phrase** generated from 256 bits of entropy, encoded using the BIP39 standard:

```
Example: apple river mountain sunset golden bridge falcon ocean
         crystal thunder meadow silver dolphin forest marble castle
         velvet compass harbor window ancient pepper rocket shield
```

1.14.2 13.2 Recovery Key Derivation

```
1. Generate: 256 bits random entropy
2. Encode:   BIP39 mnemonic (24 words, 11 bits per word)
3. Derive:   verificationKey = HKDF-SHA3-256(
                 entropy,
                 salt = accountId,
```

```
                info = "trashmail-recovery-verify"
            )
4. Hash:    verificationHash = SHA3-256(verificationKey)
5. Store:   Server stores ONLY verificationHash (32 bytes)
```

1.14.3 13.3 What the Server Stores

The server stores **only the SHA3-256 hash** of a derived verification key. It does not store:

- The recovery words
- The entropy
- The verification key itself

1.14.4 13.4 Recovery Flow

1. User enters 24-word recovery phrase
2. Client derives entropy HKDF-SHA3-256 SHA3-256 verification hash
3. Client sends verification hash to server (never the plaintext key)
4. Server compares with stored hash
5. If match: All 2FA methods are disabled, user sets up fresh authentication
6. Recovery key is revoked after single use

1.14.5 13.5 Rate Limiting

- Maximum 3 verification attempts per hour
- 60-minute lockout after exceeding limit
- One-time use: recovery key is permanently revoked after successful use

1.14.6 13.6 No Password Recovery

There is no password reset via email. If a user loses their password AND all other authentication factors (passkey + recovery key), their data is permanently inaccessible. This is the fundamental proof that zero-knowledge works — if the service could recover user data, it could also read it.

1.15 14. Passwordless Authentication (Passkeys)

1.15.1 14.1 WebAuthn PRF Extension

Aionda Mail supports FIDO2 passkeys (hardware security keys, biometric authenticators) for passwordless login and vault unlock.

The **WebAuthn PRF (Pseudo-Random Function) extension** provides a deterministic 32-byte output bound to the specific passkey and credential. This output is used to protect Shamir Share 2.

1.15.2 14.2 How It Works

```
1. Registration:
   - User creates passkey via navigator.credentials.create()
   - PRF extension generates hardware-bound output
   - Output XOR'd with Shamir Share 2 → encrypted share stored on server
```

```
2. Authentication:
   - User authenticates with passkey (biometric/PIN)
   - PRF extension reproduces same 32-byte output
   - Output XOR'd with encrypted share → Shamir Share 2 recovered
   - Combined with Share 1 (password) → Master Key reconstructed

3. Vault Unlock (passwordless):
   - If both passkey (Share 2) and password (Share 1) available → immediate unlock
   - Password verified via OPAQUE (separate from passkey auth)
```

1.15.3 14.3 Multiple Passkeys

Users can register multiple passkeys (e.g., MacBook Touch ID, iPhone Face ID, YubiKey). Each passkey independently protects its own copy of Share 2. Any single passkey combined with the password is sufficient to unlock the vault.

1.16 15. Guardian: MITM Protection & Response Signing

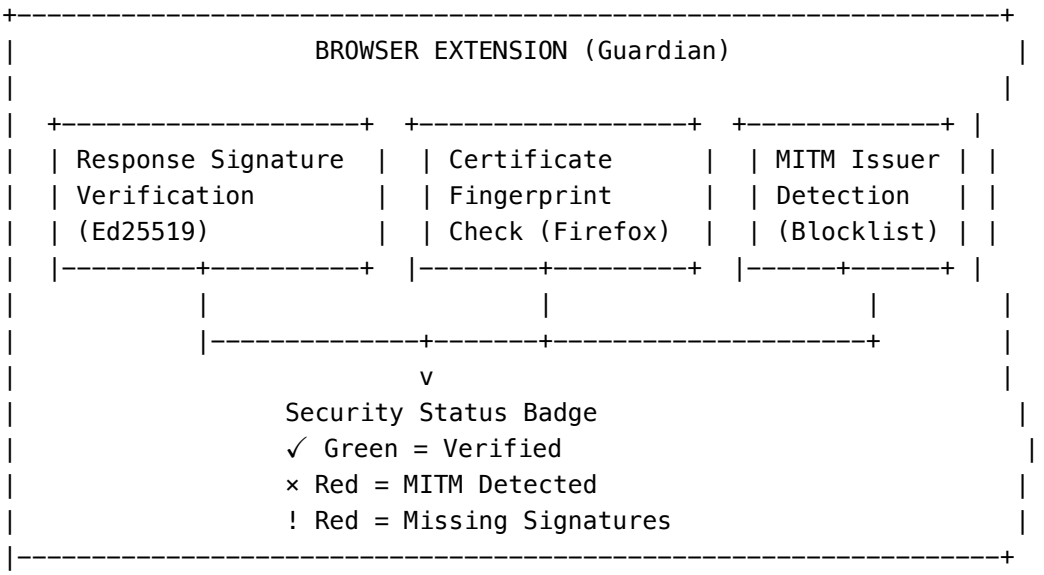
1.16.1 15.1 The Problem with Web Applications

Every web application has an inherent trust problem: the browser downloads JavaScript from the server on every visit. A man-in-the-middle (MITM) attacker — whether a compromised CDN, corporate proxy, or rogue ISP — could theoretically inject modified code that exfiltrates encryption keys.

Aionda Mail addresses this with the **Guardian module**, a browser extension component (available for Chrome and Firefox) that independently verifies server integrity.

1.16.2 15.2 Architecture Overview

The Guardian module operates inside the browser extension's Service Worker — completely independent from the web application's JavaScript. It performs three types of verification:



1.16.3 15.3 Response Signature Verification (Ed25519)

Every API response from Aionda Mail's server is cryptographically signed using **Ed25519** (Edwards-curve Digital Signature Algorithm).

Signing process (server-side):

```
1. Server generates API response body (JSON)
2. Construct signing input: responseBody + "|" + unixTimestamp
3. Sign with Ed25519 private key → 64-byte signature
4. Attach HTTP headers:
   X-Aionda-Signature: <base64(signature)>
   X-Aionda-Timestamp: <unix_timestamp>
   X-Aionda-Key-Id: <key_identifier>
```

Verification process (browser extension):

```
1. Extract signature, timestamp, and key ID from HTTP headers
2. Look up Ed25519 public key by key ID (bundled in extension)
3. Verify key has not expired (valid_from / valid_until)
4. Check timestamp freshness: |now − timestamp| ≤ 300 seconds
5. Reconstruct signing input: responseBody + "|" + timestamp
6. crypto.subtle.verify("Ed25519", publicKey, signature, data)
7. If invalid → MITM alert, red badge
```

Key properties:

- **Replay protection:** 5-minute timestamp window prevents replaying old responses
- **Tamper detection:** Any modification to the response body invalidates the signature
- **Key isolation:** Public keys are bundled inside the extension (not downloaded from the server)
- **Environment separation:** Dev keys (`dev-2026-01`) cannot be used on production URLs and vice versa

1.16.4 15.4 Ed25519 Public Key Management

Public keys are shipped with the browser extension in `public_key.json`:

```json
{
    "keys": {
        "prod-2026-01": {
            "algorithm": "Ed25519",
            "public_key": "<base64 SPKI DER>",
            "valid_from": "2026-01-13T00:00:00Z",
            "valid_until": "2027-01-13T00:00:00Z"
        }
    }
}
```

- **Key format:** SPKI DER (Subject Public Key Info, Distinguished Encoding Rules)
- **Key size:** 32 bytes (256-bit Ed25519 public key)
- **Signature size:** 64 bytes (fixed)
- **Rotation:** New keys are added before old keys expire; extension updates deliver new keys
- **No server trust:** Keys are embedded in the extension binary, not fetched from the server

1.16.5 15.5 TLS Certificate Verification (Firefox)

On Firefox, the Guardian module performs additional TLS certificate verification using the `browser.webRequest.getSecurityInfo()` API (not available in Chrome due to Manifest V3 limitations).

Verification flow:

```
1. Browser extension intercepts HTTPS response
2. Extract TLS certificate chain from browser's security info:
   - Leaf certificate fingerprint (SHA-256)
   - Issuer Distinguished Name (O=, CN=)
   - Subject (CN=)

3. Check against known MITM issuers (hardcoded blocklist):
   ZScaler, Netskope, Fortinet, Palo Alto, Blue Coat,
   Check Point, Barracuda, Sophos, WatchGuard, Cisco Umbrella
   → If match: MITM detected, show warning

4. Check against trusted issuers:
   Google Trust Services, Cloudflare, Let's Encrypt,
   DigiCert, Sectigo
   → If match AND subject matches expected domain: OK

5. If unknown issuer: Fetch server's own certificate fingerprint
   - Server connects to itself via external routing (prevents spoofing)
   - Response is Ed25519 signed (prevents MITM from lying about cert)
   - Compare issuer organization with browser's certificate issuer
   → If mismatch: MITM suspected, show warning
```

Why issuer-based validation instead of pinning? CloudFlare (used as CDN) rotates leaf certificates across edge servers. Traditional certificate pinning (matching exact fingerprints) would cause false positives. Issuer-based validation is more robust: the issuing CA is stable even when leaf certificates change.

1.16.6 15.6 Self-Certificate Fetching (Anti-Spoofing)

The server's certificate endpoint uses a clever anti-spoofing technique:

```
Server connects to cert.trashmail.com (or cert-subdomain.domain)
with SNI = mail.aionda.com

→ Forces external routing through CloudFlare
→ Receives the actual certificate that users see
→ Prevents localhost spoofing
→ Response signed with Ed25519 to prevent tampering
```

The server essentially asks "what certificate does the outside world see for my domain?" — and signs the answer so the extension can trust it.

1.16.7 15.7 Security Status Indicators

The extension displays a badge on the browser toolbar:

Badge	Color	Meaning
✓	Green	All responses verified — signatures valid
!	Orange	Using deprecated signing key (rotation pending)
×	Red	MITM detected — signature verification failed
!	Red	Missing signatures — responses not signed
[Shield]	Blue	Protected mode — no verification performed yet

1.16.8 15.8 Threat Coverage

Attack	Detection Method	Browser
Corporate MITM proxy (ZScaler, Fortinet)	Certificate issuer blocklist	Firefox
Modified API responses	Ed25519 signature verification	Chrome + Firefox
Replay attacks	5-minute timestamp window	Chrome + Firefox
CDN compromise (CloudFlare)	Response signature mismatch	Chrome + Firefox
Certificate substitution	Issuer comparison + server self-check	Firefox
Dev/prod key confusion	Environment-bound key IDs	Chrome + Firefox

1.16.9 15.9 Limitations

- **Chrome Manifest V3:** Cannot inspect TLS certificates — only response signature verification is available
- **Extension required:** Users without the extension do not benefit from Guardian protections
- **Ed25519 is not post-quantum:** Signature verification uses classical cryptography. A sufficiently powerful quantum computer could theoretically forge Ed25519 signatures.

1.17 16. Enterprise Email Archive (Blockchain)

1.17.1 16.1 Overview

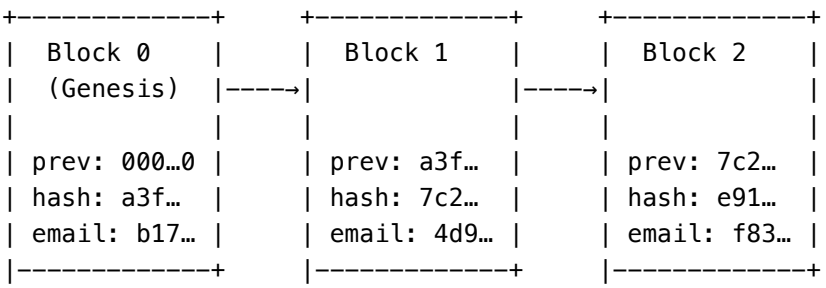
Aionda Mail's Enterprise plan includes a **GoBD-compliant email archive** secured by a cryptographic hash chain (blockchain). Every archived email becomes an immutable block in a per-company chain. Any tampering — modification, deletion, or insertion of blocks — is cryptographically detectable.

The archive combines two independent security layers:

1. **Hash chain (SHA3-256):** Guarantees integrity and immutability — proves no email was altered or removed after archival
2. **Hybrid KEM encryption (CAK):** Guarantees confidentiality — the server cannot read archived email content

1.17.2 16.2 Hash Chain Architecture

Each archived email becomes a block in a sequential, tamper-evident chain:



Block hash calculation:

```
block_hash = SHA3-256(
    prev_block_hash  || "|" ||
    timestamp        || "|" ||
    email_hash       || "|" ||
    direction        || "|" ||
    sender_domain    || "|" ||
    recipient_domain
)
```

Properties:

- **Hash algorithm:** SHA3-256 (NIST FIPS 202)
- **Genesis block:** `prev_block_hash` = 64 zeros, `block_number` = 0
- **Sequential numbering:** Enforced by database `UNIQUE KEY (company_uuid, block_number)`
- **One chain per company:** Complete isolation between enterprises
- **Email hash:** `SHA3-256(sender || recipient || timestamp || size)` — integrity proof of the original email data

1.17.3 16.3 Tamper Detection

The chain verification algorithm detects any form of tampering:

```
For each block (ordered by block_number ASC):

  1. Verify link:    block.prev_block_hash == expected_prev_hash
  2. Recalculate:    expected = SHA3-256(prev_hash | timestamp | email_hash | ...)
  3. Verify content: block.block_hash == expected
  4. Advance:        expected_prev_hash = block.block_hash

If ANY check fails → chain is broken at block N
```

Tampering Attempt	Detection
Modify email content	`email_hash` changes `block_hash` recalculation fails
Modify metadata (sender, domain, timestamp)	Included in hash input `block_hash` mismatch
Delete a block	Next block's `prev_block_hash` becomes orphaned

Tampering Attempt	Detection
Insert a block	Breaks sequential `block_number` + `prev_block_hash` chain
Reorder blocks	`UNIQUE KEY` constraint + sequential verification prevents this
Replace entire chain	Genesis block hash would differ from any external backup

Verification result reports the exact block number where tampering was detected, with expected vs. actual hash values for forensic analysis.

1.17.4 16.4 Company Archive Key (CAK) — Zero-Knowledge Encryption

Archive contents are encrypted end-to-end using a **Company Archive Key** — a Hybrid KEM keypair (X25519 + ML-KEM-1024) generated client-side by the company owner.

```
Company Owner's Browser                          Server
──────────────────────                           ──────

1. Generate Hybrid KEM keypair (client-side):
   X25519 keypair (32 + 32 bytes)
   ML-KEM-1024 keypair (1568 + 3168 bytes)

2. Derive wrapping key from password:
   wrappingKey = HKDF-SHA256(
     password,
     salt = "trashmail-archive-{account_id}",
     info = "trashmail-archive-key-wrap",
     length = 32
   )

3. Wrap private keys:
   AES-256-GCM(x25519_priv || mlkem_priv, wrappingKey)

4. Send to server:                          →    Store:
   • Public keys (plaintext)                        archive_x25519_pub
   • Wrapped private keys (encrypted)               archive_mlkem_pub
                                                    wrapped_archive_key
```

Key distribution to other employees (Admin, Compliance Officer):

1. Owner decrypts CAK private keys with their password
2. Owner re-wraps private keys with target employee's password-derived key
3. Server stores the re-wrapped copy on the employee's record
4. Each authorized employee has their own independently wrapped copy

The server never sees the CAK private keys in plaintext.

1.17.5 16.5 What Gets Encrypted

When an email is archived, two layers of encryption are applied:

Encrypted metadata (AES-256-GCM with Hybrid KEM):

```
{
  "d": "INBOUND",
  "s": "user@example.com",
  "r": "admin@company.de",
  "sd": "example.com",
  "rd": "company.de",
  "sz": 45000,
  "ts": "2026-02-27T10:30:00Z",
  "ha": true,
  "ac": 3,
  "en": "John Doe"
}
```

Encrypted email content (separate Hybrid KEM key wrapping):

```
{
  "subject": "Meeting notes",
  "body": "<html>...</html>",
  "from": "sender@domain.com",
  "to": "recipient@company.de"
}
```

Zero-knowledge enforcement: After encryption, the plaintext metadata fields in the database (sender_address, recipient_address, domains) are replaced with their SHA3-256 hashes. The server stores only hashes — the original values exist only inside the encrypted blobs.

1.17.6 16.6 Audit Trail

Every action on the archive is logged in an **independent audit chain** (also hash-chained with SHA3-256):

Action	When Logged
`EMAIL_RECEIVED` / `EMAIL_SENT` / `DRAFT_ARCHIVED`	Email archived
`VIEW_EMAIL` / `VIEW_ATTACHMENT`	Employee reads archived email
`SEARCH_ARCHIVE`	Search performed
`EXPORT_EMAIL` / `EXPORT_REPORT`	Data exported
`VERIFY_CHAIN` / `CHAIN_VERIFIED_OK` / `CHAIN_VERIFIED_BROKEN`	Integrity check
`LEGAL_HOLD_SET` / `LEGAL_HOLD_RELEASED`	Legal hold toggled
`ARCHIVE_DECRYPT`	CAK used to decrypt content
`ADMIN_ACCESS`	Administrative action

Each audit entry records: actor (UUID + role), IP address, session ID, target email hash, and whether the chain was valid at the time of access.

1.17.7 16.7 Legal Hold & Retention

- **Retention period:** Configurable per company (default: 10 years), calculated per email as `archived_at + retention_years`
- **Legal hold:** Individual emails can be placed under legal hold, preventing deletion until released. Includes reason, actor, and timestamp.
- **GoBD compliance:** The combination of immutable hash chain, complete audit trail, configurable retention, and legal hold satisfies the requirements of the German GoBD (Grundsätze zur ordnungsmäßigen Führung und Aufbewahrung von Büchern, Aufzeichnungen und Unterlagen in elektronischer Form sowie zum Datenzugriff).

1.17.8 16.8 Forensic Export

Authorized users (Owner, Admin) can export the complete chain state for independent verification:

- Full chain data with all block hashes
- Verification result (valid/broken, broken block number if applicable)
- Expected vs. actual hash values for forensic analysis
- Last 50 audit log entries
- JSON format for external re-verification with any SHA3-256 implementation

---

1.18 17. What the Server Sees — and What It Does Not

This section explicitly documents the zero-knowledge boundary.

1.18.1 17.1 The Server CAN See

Data	Why Visible	Mitigation
IP address	TCP/IP requirement	Use VPN/Tor if desired
Timestamps	Email reception time	Inherent to email protocol
Encrypted email blobs	Stored for retrieval	AES-256-GCM encrypted, key unknown to server
Padded ciphertext sizes	Storage requirement	Bucket padding hides actual sizes
Recipient DEA address	Routing requirement	DEA is disposable, not the real address
Account existence	Authentication flow	User enumeration protection deployed
Public keys	Required for encryption by server	Public by definition, not sensitive
Encrypted Shamir shares	Storage for user	XOR'd with keys server doesn't know
OPAQUE records	Authentication protocol	Not password hashes, encrypted at rest

1.18.2 17.2 The Server CANNOT See

Data	Why Invisible
Email content (subject, body, headers)	Encrypted with ephemeral keys wrapped via Hybrid KEM
User password	OPAQUE — password never transmitted
Master key	Reconstructed only in browser from Shamir shares
Vault private keys	Encrypted with master key before storage
Email ephemeral keys	Wrapped with Hybrid KEM, server lacks private keys
Recovery key / mnemonic	Only SHA3-256 hash of derived key stored
Passkey PRF outputs	Hardware-bound, never leave authenticator
Folder names	Encrypted with folder-specific keys
Email signatures	Encrypted with master key
API request content	Encrypted via /e transport layer
API response content	Encrypted before transmission

1.18.3 17.3 Cryptographic Guarantee

Even with full access to:

- The complete database
- All network traffic
- The server's source code and configuration
- All OPAQUE records and server keys

…an attacker **cannot** decrypt a single email without the user's password (or passkey + recovery key). This is not a policy — it is a mathematical impossibility enforced by the cryptographic design.

1.19 18. Algorithm Reference

1.19.1 18.1 Complete Algorithm Table

Component	Algorithm	Parameters	Standard
Password authentication	OPAQUE	RFC 9807, aPAKE	RFC 9807
Password key derivation	PBKDF2-SHA256	600,000 iterations, 32B salt, 32B output	NIST SP 800-132
Vault encryption	AES-256-GCM	256-bit key, 96-bit nonce, 128-bit tag	NIST SP 800-38D
Classical key exchange	X25519	Curve25519, 256-bit	RFC 7748
Post-quantum KEM	ML-KEM-1024	Kyber-1024, NIST Level 5	NIST FIPS 203
Hybrid key derivation	HKDF-SHA256	64B IKM, info="trashmail-hybrid-kem-v1"	RFC 5869
Secret sharing	Shamir SSS	k=2, n=3, GF(2^8)	Shamir (1979)

Component	Algorithm	Parameters	Standard
Recovery key encoding	BIP39	256-bit entropy, 24 words	BIP-0039
Recovery key derivation	HKDF-SHA3-256	Account-bound salt	NIST FIPS 202
Recovery key verification	SHA3-256	32-byte output	NIST FIPS 202
OPAQUE record encryption	AES-256-GCM	Server-side at-rest encryption	NIST SP 800-38D
Passkey vault unlock	WebAuthn PRF	HMAC-based, hardware-bound	WebAuthn Level 2
Compression	gzip	Level 6	RFC 1952
Bucket padding	Custom	17 sizes (256B–16MB), 0xDEAD magic	—
Response signing	Ed25519	256-bit key, 512-bit signature	RFC 8032
Archive hash chain	SHA3-256	Per-block hash, sequential linking	NIST FIPS 202
Archive key wrapping (CAK)	HKDF-SHA256 + AES-256-GCM	Password-derived wrapping key	RFC 5869 / NIST SP 800-38D
Certificate verification	SHA-256	TLS cert fingerprint comparison	—
Email threading	SHA-256	Hash of Message-ID	NIST FIPS 180-4

1.19.2 18.2 Security Levels

Algorithm	Classical Security	Post-Quantum Security
X25519	128-bit	Broken by Shor's algorithm
ML-KEM-1024	256-bit equivalent	NIST Level 5 (≈AES-256)
AES-256-GCM	256-bit	128-bit (Grover's algorithm)
SHA-256	256-bit	128-bit (Grover's algorithm)
SHA3-256	256-bit	128-bit (Grover's algorithm)
Hybrid KEM (combined)	128-bit (X25519 bound)	Level 5 (ML-KEM bound)

1.20 19. Comparison with Other Providers

Feature	Aionda Mail	Tuta Mail	Proton Mail
Country	Germany (Stuttgart)	Germany (Hannover)	Switzerland
Zero-Knowledge	Yes (OPAQUE + client-side crypto)	Yes	Yes
Post-Quantum	Yes (ML-KEM-1024 + X25519 Hybrid)	Yes (Kyber-based)	In development

Feature	Aionda Mail	Tuta Mail	Proton Mail
Password protocol	OPAQUE (RFC 9807) — password never leaves browser	bcrypt (password sent to server over TLS)	SRP-based
Subject encrypted	Yes	Yes	No
Headers encrypted	Yes	Partial	No
Contact names encrypted	Yes (in vault)	Yes	No
Disposable email addresses	Yes (core feature, unlimited for Plus)	No	Yes (via SimpleLogin)
Browser addon	Yes (Chrome + Firefox)	No	Via SimpleLogin
Folder sharing	Yes (Hybrid KEM per recipient)	Limited	Yes
Open source client	No	Yes	Yes
Security audit	Planned	Yes	Yes
Password recovery	No (by design)	No (by design)	No (by design)
Passkey support	Yes (FIDO2 + PRF)	Yes	Yes
PGP support	Yes (incoming + outgoing)	No (own protocol)	Yes (OpenPGP)
GoBD-compliant email archive	Yes (SHA3-256 hash chain + Hybrid KEM)	No	No
MITM detection (browser ext.)	Yes (Ed25519 signatures + TLS check)	No	No
Perfect Forward Secrecy (API)	Yes (per-request ephemeral keys)	Unknown	Unknown
Email size obfuscation	Yes (bucket padding)	Unknown	No

1.21 20. Limitations & Honest Boundaries

1.21.1 20.1 Web Application Trust Model

Aionda Mail is a web application. On every page load, the browser downloads JavaScript from our servers. A sophisticated attacker who compromises our servers could theoretically serve modified JavaScript that exfiltrates keys.

Current mitigations:

- Subresource Integrity (SRI) hashes on all script tags

- Content Security Policy (CSP) headers restrict script sources
- All critical cryptographic code is included in the main application bundle
- **Guardian browser extension** (Section 14): Ed25519 signature verification on all API responses detects server-side tampering; TLS certificate verification (Firefox) detects MITM proxies

Planned mitigations:

- Service Worker caching for offline operation (reduces trust-on-load frequency)

1.21.2 20.2 Metadata Visibility

While email content is fully encrypted, certain metadata is visible to the server:

- When emails were received (timestamps)
- Which DEA address received the email
- Approximate email size (within bucket boundaries)
- Account activity patterns

1.21.3 20.3 Email Processing Log

For diagnostic purposes, Aionda Mail includes an optional **email processing log** that can temporarily store the raw content of incoming emails. This feature is configurable per disposable email address (DEA) and can be enabled or disabled in the DEA settings ("Log email content").

When enabled (opt-in per DEA):

- The full raw SMTP message (headers + body) is stored in plaintext on the server
- Automatic deletion after a short retention period (less than 7 days)
- Accessible only to the account owner via authenticated API
- Purpose: troubleshooting delivery issues, verifying forwarding, reviewing spam filtering decisions

When disabled:

- No email content is stored in the processing log
- Only metadata is logged (sender address, timestamp, delivery status)
- Vault encryption remains the sole storage mechanism

Important: This processing log is independent of the encrypted vault. Emails stored in the vault are always encrypted with Hybrid KEM regardless of the log setting. The processing log exists as a legacy feature from the email forwarding system and provides operational transparency. Users who require strict zero-knowledge storage for all emails should disable this option.

1.21.4 20.4 External Email Security

Emails sent to or received from non-Aionda addresses travel through the standard email infrastructure (SMTP). While stored encrypted in the vault, the email content was visible during transit unless PGP encryption was used.

1.21.5 20.5 No Key Escrow

There is no master key, backdoor, or recovery mechanism available to Aionda GmbH. If a user loses their password and all recovery methods, their data is permanently lost. This is an

intentional design decision that proves the integrity of the zero-knowledge model.

1.22 21. Roadmap

Milestone	Status	Target
Zero-Knowledge Architecture	Completed	—
Post-Quantum Hybrid KEM (ML-KEM-1024)	Completed	—
OPAQUE Authentication (RFC 9807)	Completed	—
Shamir Secret Sharing (2-of-3)	Completed	—
Encrypted API Transport Layer	Completed	—
Passkey/WebAuthn PRF Support	Completed	—
End-to-End Encrypted Calendar	Completed	—
GoBD-Compliant Email Archive (Blockchain)	Completed	—
Guardian MITM Protection (Ed25519)	Completed	—
TLS Certificate Verification (Firefox)	Completed	—

1.23 Document History

Version	Date	Changes
1.0	March 2026	Initial publication
1.1	April 2026	New chapter 10: Vault Drive (per-file-key architecture, sharing via key rewrap)
1.2	April 2026	Section 10.11: External Sharing — public share links with hybrid KEM envelopes, unlock_token flow, Argon2id password mode, URL fragment for link-only, tamper-evident audit chain (EXT_SHARE_*), and user-chosen link distribution

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1.24 Contact

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This document describes the security architecture of Aionda Mail as of April 2026. Cryptographic systems evolve — this document will be updated as the architecture changes.