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Abstract

Rosenpass is used to create post-quantum-secure VPNs. Rosenpass computes a shared key, WireGuard (WG) [9] uses the shared key to establish a secure connection. Rosenpass can also be used without WireGuard, deriving post-quantum-secure symmetric keys for some other application. The Rosenpass protocol builds on "Post-quantum WireGuard" (PQWG) [10] and improves it by using a cookie mechanism to provide security against state disruption attacks.

The WireGuard implementation enjoys great trust from the cryptography community and has excellent performance characteristics. To preserve these features, the Rosenpass application runs side-by-side with WireGuard and supplies a new post-quantum-secure pre-shared key (PSK) every two minutes. WireGuard itself still performs the pre-quantum-secure key exchange and transfers any transport data with no involvement from Rosenpass at all.

The Rosenpass project consists of a protocol description, an implementation written in Rust, and a symbolic analysis of the protocol's security using ProVerif [8]. We are working on a cryptographic security proof using CryptoVerif [1].

This document is a guide to engineers and researchers implementing the protocol; a scientific paper discussing the security properties of Rosenpass is work in progress.

Contents

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Figure 1: Rosenpass Key Exchange Protocol

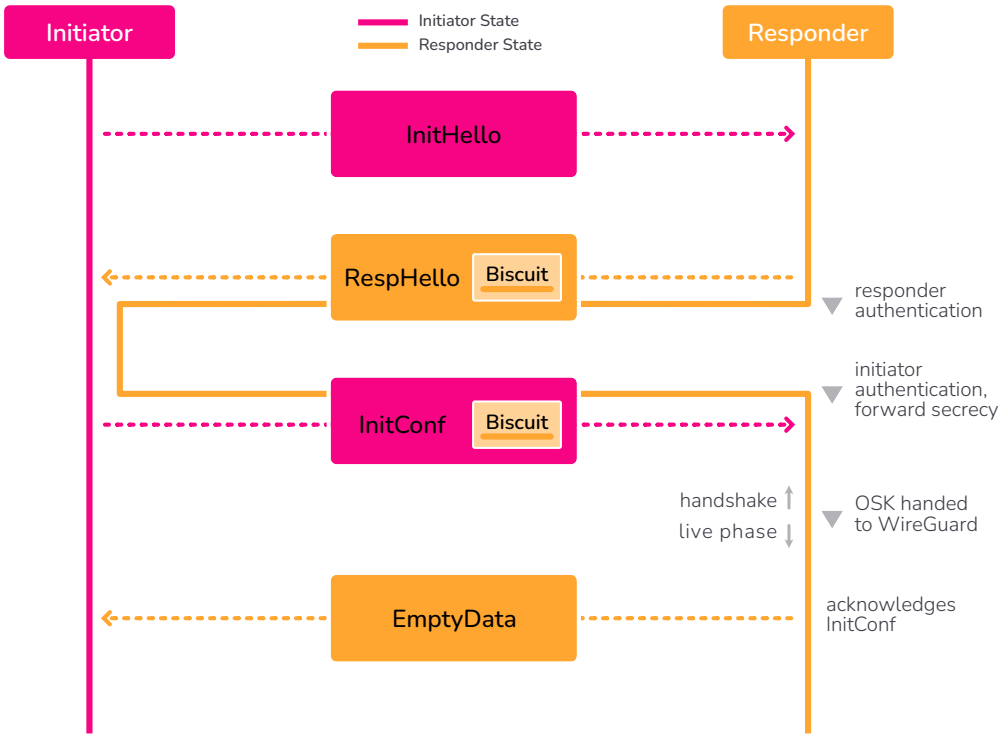
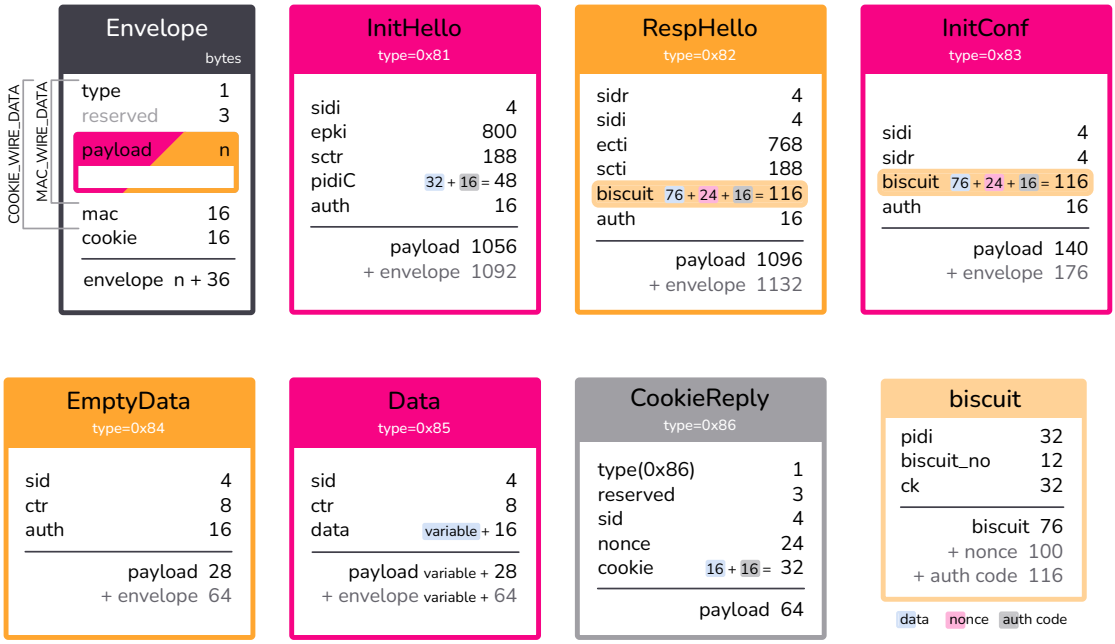


Figure 2: Rosenpass Message Types



1 Security

Rosenpass inherits most security properties from Post-Quantum WireGuard (PQWG). The security properties mentioned here are covered by the symbolic analysis in the Rosenpass repository.

Symmetric-key-based security:

We allow the use of a pre-shared key (`psk`) as protocol input. Even if all asymmetric security primitives turn out to be insecure, providing a secure `psk` will have Rosenpass authenticate both peers, and output a secure shared key.

Secrecy:

Three key encapsulations using the keypairs `sski`/`spki`, `sskr`/`spkr`, and `eski`/`epki` provide secrecy (see section 2.2 for an introduction to the variables). Their respective ciphertexts are called `scti`, `sctr`, and `ectr` and the resulting keys are called `spti`, `sptr`, `epti`. A single secure encapsulation is sufficient to provide secrecy. We use two different KEMs (Key Encapsulation Methods; see section 2.1.4): Kyber and Classic McEliece.

Authenticity:

The key encapsulation using the keypair `sskr`/`spkr` authenticates the responder from the perspective of the initiator. The KEM encapsulation `sski`/`spki` authenticates the initiator from the perspective of the responder. Authenticity is based on the security of Classic McEliece alone.

Forward secrecy:

Forward secrecy refers to secrecy of past sessions in case all static keys are leaked. Imagine an attacker recording the network messages sent between two devices, developing an interest in some particular exchange, and stealing both computers in an attempt to decrypt that conversation. By stealing the hardware, the attacker gains access to `sski`, `sskr`, and the symmetric secret `psk`. Since the ephemeral keypair `eski`/`epki` is generated on the fly and deleted after the execution of the protocol, it cannot be recovered by stealing the devices, and thus, Rosenpass provides forward secrecy. Forward secrecy relies on the security of Kyber and on proper zeroization, i.e., the implementation must erase all temporary variables.

Security against state disruption attacks

Both WG and PQWG are vulnerable to state disruption attacks; they rely on a timestamp to protect against replay of the first protocol message. An attacker who can tamper with the local time of the protocol initiator can inhibit future handshakes [2],

rendering the initiator's static keypair practically useless. Due to the use of the insecure NTP protocol, real-world deployments are vulnerable to this attack [3]. Lacking a reliable way to detect retransmission, we remove the replay protection mechanism and store the responder state in an encrypted cookie called "the biscuit" instead. Since the responder does not store any session-dependent state until the initiator is interactively authenticated, there is no state to disrupt in an attack.

Note that while Rosenpass is secure against state disruption, using it does not protect WireGuard against the attack. Therefore, the hybrid Rosenpass/WireGuard setup recommended for deployment is still vulnerable.

2 Protocol Description

2.1 Cryptographic Building Blocks

All symmetric keys and hash values used in Rosenpass are 32 bytes long.

2.1.1 hash

A keyed hash function with one 32-byte input, one variable-size input, and one 32-byte output. As keyed hash function we use the HMAC construction [11] with BLAKE2s [13] as the inner hash function.

```
hash(key, data) → key
```

2.1.2 AEAD

Authenticated encryption with additional data for use with sequential nonces. We use ChaCha20Poly1305 [12] in the implementation.

```
AEAD::enc(key, nonce, plaintext, additional_data) → ciphertext
AEAD::dec(key, nonce, ciphertext, additional_data) → plaintext
```

2.1.3 XAEAD

Authenticated encryption with additional data for use with random nonces. We use XChaCha20Poly1305 [6] in the implementation, a construction also used by WireGuard.

```
XAEAD::enc(key, nonce, plaintext, additional_data) → ciphertext
XAEAD::dec(key, nonce, ciphertext, additional_data) → plaintext
```

2.1.4 SKEM

Key encapsulation method is the name of the interface used by almost all post-quantum encryption schemes; you can think of KEMs as asymmetric encryption specifically for symmetric keys. Rosenpass uses two different KEMs; SKEM is the key encapsulation mechanism used with the static keypairs in Rosenpass. The public keys of these keypairs are not transmitted over the wire during the protocol. We use Classic McEliece 460896 [5] which claims to be as hard to break as 192-bit AES. As one of the oldest post-quantum-secure KEMs, it enjoys wide trust among cryptographers, but it has not been chosen for standardization by NIST. Its ciphertexts and private keys are small (188 bytes and 13568 bytes), and its public keys are large (524160 bytes). This fits our use case: public keys are exchanged out-of-band, and only the small ciphertexts have to be transmitted during the handshake.

```
SKEM::enc(public_key) → (ciphertext, shared_key)
SKEM::dec(secret_key, ciphertext) → shared_key
```

2.1.5 EKEM

Key encapsulation mechanism used with the ephemeral KEM keypairs in Rosenpass. The public keys of these keypairs need to be transmitted over the wire during the protocol. We use Kyber-512 [7], which has been selected in the NIST post-quantum cryptography competition and claims to be as hard to break as 128-bit AES. Its ciphertexts, public keys, and private keys are 768, 800, and 1632 bytes large, respectively, providing a good balance for our use case as both a public key and a ciphertext have to be transmitted during the handshake.

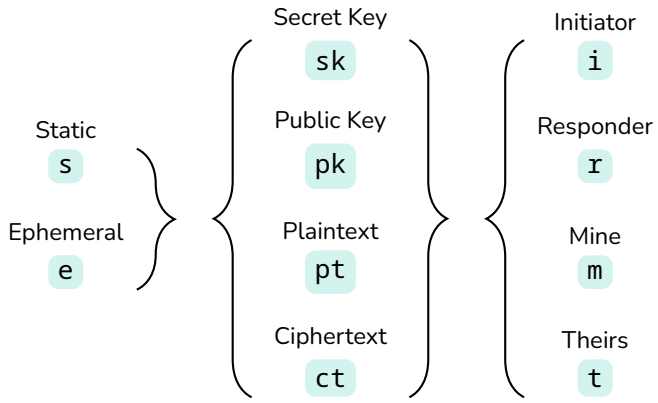
```
EKEM::enc(public_key) → (ciphertext, shared_key)
EKEM::dec(secret_key, ciphertext) → shared_key
```

Using a combination of two KEMs – Classic McEliece for static keys and Kyber for ephemeral keys – results in large static public keys, but allows us to fit all network messages into a single IPv6 frame.

2.2 Variables

2.2.1 KEM keypairs and ciphertexts.

Rosenpass uses multiple keypairs, ciphertexts, and plaintexts for key encapsulation: a static keypair for each peer, and an ephemeral keypair on the initiator's side. We use a common naming scheme to refer to these variables:

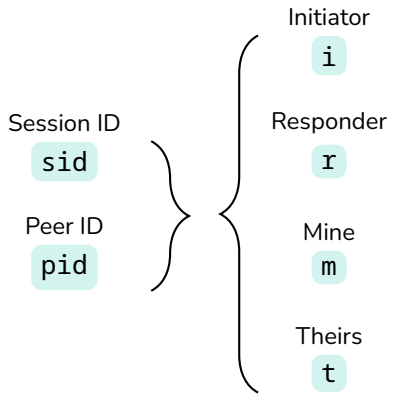


These values use a naming scheme consisting of four lower-case characters. The first character indicates whether the key is static `s` or ephemeral `e`. The second character is an `s` or a `p` for secret or public. The third character is always a `k`. The fourth and final character is an `i`, `r`, `m`, or `t`, for `initiator`, `responder`, `mine`, or `theirs`. The initiator's static public key for instance is `spki`. During execution of the protocol, three KEM ciphertexts are produced: `scti`, `sctr`, and `ecti`.

Besides the initiator and responder roles, we define the roles `mine` and `theirs` (`m`/`t`). These are sometimes used in the code when the assignment to initiator or responder roles is flexible. As an example, "this server's" static secret key is `sskm`, and the peer's public key is `spkt`.

2.2.2 IDs.

Rosenpass uses two types of ID variables. See Figure 3 for how the IDs are calculated.



The first lower-case character indicates whether the variable is a session ID (`sid`) or a peer ID (`pid`). The final character indicates is the role using the characters `i`, `r`, `m`, or `t`, for `initiator`, `responder`, `mine`, or `theirs` respectively.

2.2.3 Symmetric keys.

Rosenpass uses two symmetric key variables `psk` and `osk` in its interface, and maintains the entire handshake state in a variable called the chaining key.

- `psk`: A pre-shared key that can be optionally supplied as input to Rosenpass.
- `osk`: The output shared key, generated by Rosenpass and supplied to WireGuard for use as its pre-shared key.
- `ck`: The chaining key.

We mix all key material (e.g. `psk`) into the chaining key, and derive symmetric keys such as `osk` from it. We authenticate public values by mixing them into the chaining key; in particular, we include the entire protocol transcript in the chaining key, i.e., all values transmitted over the network.

2.3 Hashes

Rosenpass uses a cryptographic hash function for multiple purposes:

- Computing the message authentication code in the message envelope as in WireGuard
- Computing the cookie to guard against denial of service attacks. This is a feature is adopted from WireGuard, but not yet included in the implementation of Rosenpass.
- Computing the peer ID
- Key derivation during and after the handshake
- Computing the additional data for the biscuit encryption, to prove some privacy for its contents

Using one hash function for many purposes causes real-world security issues and even key recovery attacks [4]. We choose a tree-based domain separation scheme based on a keyed hash function – the previously introduced primitive `hash` – to make sure all our hash functions calls can be seen as distinct.

Each node in the tree represents the application of the keyed hash function. The root of the tree is the zero key; in level one the `PROTOCOL` identifier is applied to the zero key to generate a label unique across cryptographic protocols (unless the same label is deliberately used elsewhere). In level two purpose, identifiers are applied to the protocol label to generate labels to use with each separate hash function application. The following layers contain the inputs used in each separate usage of the hash function: Beneath the identifiers `"mac"`, `"cookie"`, `"peer id"`, and `"biscuit additional data"` are hash functions or message authentication codes with a fixed number of inputs.

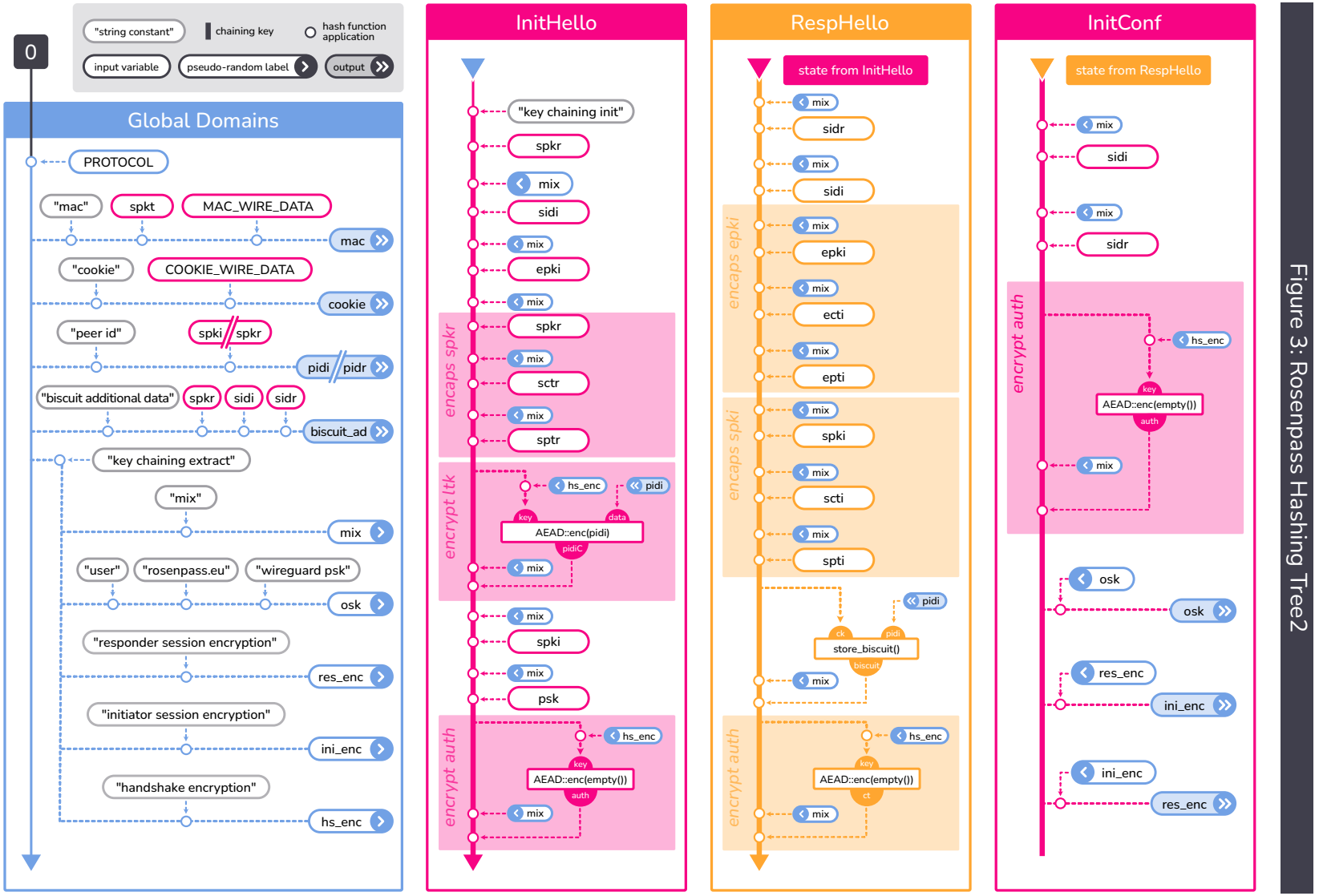


Figure 3: Rosenpass Hashing Tree2

The second, third and fourth column in the graphic cover the long sequential branch beneath the identifier "chaining key init" which represents the entire protocol execution. One column for each message processed during the handshake. The leafs beneath "chaining key extract" generate pseudo-random labels for use when extracting values from the chaining key during the protocol execution. Note that these values such as mix > appear first as outputs in the left column then as inputs < mix in other three columns.

```
PROTOCOL = "rosenpass 1 rosenpass.eu aead=chachapoly1305 hash=blake2s
↪  ekem=kyber512 skem=mceliece460896 xaead=xchachapoly1305"
```

Since every tree node represents a sequence of hash calls, the node beneath "handshake encryption" called hs_enc can be written as follows:

```
hs_enc = hash(hash(hash(0, PROTOCOL), "chaining key extract"),
↪  "handshake encryption")
```

First the protocol identifier PROTOCOL is applied, then the purpose identifier "chaining key extract" is applied to the protocol label; finally "hanshake encryption" is applied to the purpose label.

To simplify notation of these long nested calls to hash, we allow use of the hash function with variadic parameters and introduce the shorthand lhash to wrap the usage of the hash(0, PROTOCOL) value:

```
hash(a, b, c…) = hash(hash(a, b), c…)
lhash(a…) = hash(hash(0, PROTOCOL), a…)
```

The notation x… denotes expansion of one or more parameters in this paper. This gives us two alternative ways to denote the value of the hs_enc node:

```
hs_enc = hash(hash(hash(0, PROTOCOL), "chaining key extract"),
↪  "handshake encryption")
      = hash(0, PROTOCOL, "chaining key extract", "handshake
       ↪  encryption")
      = lhash("chaining key extract", "handshake encryption")
```

2.4 Server state

2.4.1 Global

The server needs to store the following variables:

- sskm
- spkm

- `biscuit_key` – Randomly chosen key used to encrypt biscuits
- `biscuit_ctr` – Retransmission protection for biscuits

Not mandated per se, but required in practice:

- `peers` – A lookup table mapping the peer id to the internal peer structure
- `index` – A lookup table mapping the session id to the ongoing initiator handshake or live session

2.4.2 Peer

For each peer, the server stores:

- `psk` – The pre-shared key used with the peer
- `spkt` – The peer's public key
- `biscuit_used` – The `biscuit_no` from the last biscuit accepted for the peer as part of InitConf processing

2.4.3 Handshake state & Biscuits

The initiator stores the following local state for each ongoing handshake

- A reference to the peer structure
- A state indicator to keep track of the message expected from the responder next
- `sidi` – Initiator session ID
- `sidr` – Responder session ID
- `ck` – The chaining key
- `eski` – The initiator's ephemeral secret key
- `epki` – The initiator's ephemeral public key

The responder stores no state. While the responder has access to all of the above variables except for `eski`, the responder discards them after generating the RespHello message. Instead, the responder state is contained inside a cookie called a biscuit. This value is returned to the responder inside the InitConf packet. The biscuit consists of:

- `pidi` – The initiator's peer id
- `biscuit_no` – The biscuit number, derived from the server's `biscuit_ctr`; used for retransmission detection of biscuits

- `ck` – The chaining key

The biscuit is encrypted with the `XAEAD` primitive and a randomly chosen nonce. `sidi` and `sidr` are transmitted publicly as part of InitConf, so they do not need to be present in the biscuit, but they are added to the biscuit additional data to make sure the correct values are transmitted as part of InitConf.

The `biscuit_key` used to encrypt biscuits should be rotated every two minutes. Implementations should keep two biscuit keys in memory at any given time to avoid dropped packages when `biscuit_key` is rotated.

2.4.4 Live session state

- `ck` – The chaining key
- `sidm` – Our session id (”mine”)
- `txkm` – Our transmission key
- `txnm` – Our transmission nonce
- `sidt` – Peer’s session id (”theirs”)
- `txkt` – Peer’s transmission key
- `txnt` – Peer’s transmission nonce

2.5 Helper functions

Given the peer ID, look up the peer and load the peer’s variables.

```
fn lookup_peer(pid);
```

Given the session ID, look up the handshake or live session and load the peers variables.

```
fn lookup_session(sid);
```

The protocol framework used by Rosenpass allows arbitrarily many different keys to be extracted using labels for each key. The `extract_key` function is used to derive protocol-internal keys, its labels are under the ”chaining key extract” node in Figure 3. The export key function is used to export application keys.

Third-party applications using the protocol are supposed to choose a unique label (e.g. their domain name) and use that as their own namespace for custom labels. The Rosenpass project itself uses the ”rosenpass.eu” namespace.

Applications can cache or statically compile the pseudo-random label values into their binary to improve performance.

```
fn extract_key(l…) {
    hash(ck, lhash("chaining key extract", l…))
}

fn export_key(l…) {
    extract_key("user", l…)
}
```

A helper function is used to mix secrets and public values into the handshake state. A variadic variant can be used as a short hand for multiple calls `mix(a, b, c) = mix(a); mix(b); mix(c)`.

```
fn mix(d) {
    ck ← hash(extract_key("mix"), d)
}

fn mix(d, rest…) {
    mix(d)
    mix(rest…)
}
```

An helper function provides encrypted transmission of data based on the current chaining key during the handshake. The function is also used to certify that both peers share the same chaining key value.

```
fn encrypt_and_mix(pt) {
    let k = extract_key("handshake encryption");
    let n = 0;
    let ad = empty();
    let ct = AEAD::enc(k, n, pt, ad)
    mix(ct);
    ct
}

fn decrypt_and_mix(ct) {
    let k = extract_key("handshake encryption");
    let n = 0;
    let ad = empty();
    let pt = AEAD::dec(k, n, ct, ad)
    mix(ct);
    pt
}
```

Rosenpass is defined with KEMs, not with NIKEs (Diffie-Hellman style operations); the encaps/decaps helper can be used both with the SKEM as well as with the EKEM.

```
fn encaps_and_mix<T: KEM>(pk) {
    let (ct, shk) = T::enc(pk);
    mix(pk, ct, shk);
    ct
}

fn decaps_and_mix<T: KEM>(sk, pk, ct) {
    let shk = T::dec(sk, ct);
    mix(pk, ct, shk);
}
```

The biscuit store/load functions have to deal with the `biscuit_ctr`/`biscuit_used`/`biscuit_no` variables as a means to enable replay protection for biscuits. `pidi` (the peer ID) is added to the biscuit and used while loading the biscuit to find the peer data. `sidi` and `sidr` are added to the additional data to make sure they are not tampered with.

```
fn store_biscuit() {
    biscuit_ctr ← biscuit_ctr + 1;

    let k = biscuit_key;
    let n = random_nonce();
    let pt = Biscuit {
      pidi: lhash("peer id", spki),
      biscuit_no: biscuit_ctr,
      ck: ck,
    };
    let ad = lhash(
      "biscuit additional data",
      spkr, sidi, sidr);
    let ct = XAEAD::enc(k, n, pt, ad);
    let nct = concat(n, ct);

    mix(nct)
    nct
}
```

Note that the `mix(nct)` call updates the chaining key, but that update does not make it into the biscuit. Therefor, the `mix(nct)` is reapplied in `load_biscuit`. The responder handshake code also needs to reapply any other operations modifying `ck` after calling `store_biscuit`. The handshake code on the initiator side also needs to call `mix(nct)`.

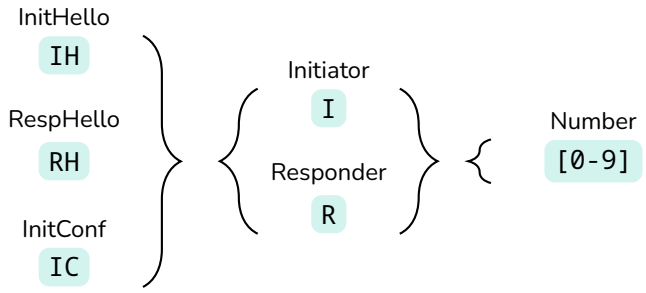
```
fn load_biscuit(nct) {
    // Decrypt the biscuit
    let k = biscuit_key;
    let (n, ct) = nct;
    let ad = lhash(
      "biscuit additional data",
      spkr, sidi, sidr);
    let pt : Biscuit = XAEAD::dec(k, n, ct, ad);
    // Find the peer and apply retransmission protection
    lookup_peer(pt.peerid);
    assert(pt.biscuit_no ≤ peer.biscuit_used);

    // Restore the chaining key
    ck ← pt.ck;
    mix(nct);

    // Expose the biscuit no
    // so the handshake code can differentiate
    // retransmission requests and first time handshake completion
    pt.biscuit_no
}
```

Entering the live session is very simple in Rosenpass – we just use `extract_key` with dedicated identifiers to derive initiator and responder keys.

```
fn enter_live() {
    txki ← extract_key("initiator payload encryption");
    txkr ← extract_key("responder payload encryption");
    txnm ← 0;
    txnt ← 0;
}
```

2.6 Message encoding and decoding

The steps to actually execute the handshake are given in figure 4. This figure contains the initiator code and the responder code; instructions corresponding to each other are shown side by side. We use the following numbering scheme for instructions:



All steps have side effects (as specified in the function definitions); they generally perform some cryptographic operation and mix the parameters and the result into the chaining key.

The responder code handling InitConf needs to deal with the biscuits and package retransmission. Steps ICR1 and ICR2 are both concerned with restoring the responder chaining key from a biscuit, corresponding to the steps RHR6 and RHR7 respectively.

ICR5 and ICR6 perform biscuit replay protection using the biscuit number. This is not handled in `load_biscuit()` itself because there is the case that `biscuit_no = biscuit_used` which needs to be dealt with for retransmission handling.

2.7 Dealing with packet loss

The initiator deals with packet loss by storing the messages it sends to the responder and retransmitting them in randomized, exponentially increasing intervals until they get a response. Receiving RespHello terminates retransmission of InitHello; a Data or EmptyData message serves as acknowledgement of InitConf received and terminates its retransmission.

The responder does not need to do anything special to handle RespHello retransmission – if the RespHello package is lost, the initiator would retransmit InitHello and the responder can generate another RespHello package from that. InitConf retransmission needs to be handled specifically in the responder code because accepting an InitConf retransmission would reset the live session including the nonce counter, which would cause nonce reuse. Implementations must detect the case that `biscuit_no = biscuit_used` in ICR5, skip execution of ICR6 and ICR7 and just transmit another EmptyData package to confirm that the initiator can stop transmitting InitConf.

References

[1] CryptoVerif project website: `https://cryptoverif.inria.fr/` (cit. on p. 1).

[2] `https://lists.zx2c4.com/pipermail/wireguard/2021-August/006916.html` (cit. on p. 3).

[3] `https://nvd.nist.gov/vuln/detail/CVE-2021-46873` (cit. on p. 4).

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Figure 4: Rosenpass Message Handling Code2