An Efficient and Generic Construction for Signal's Handshake (X3DH)

Post-Quantum, State Leakage Secure, and Deniable

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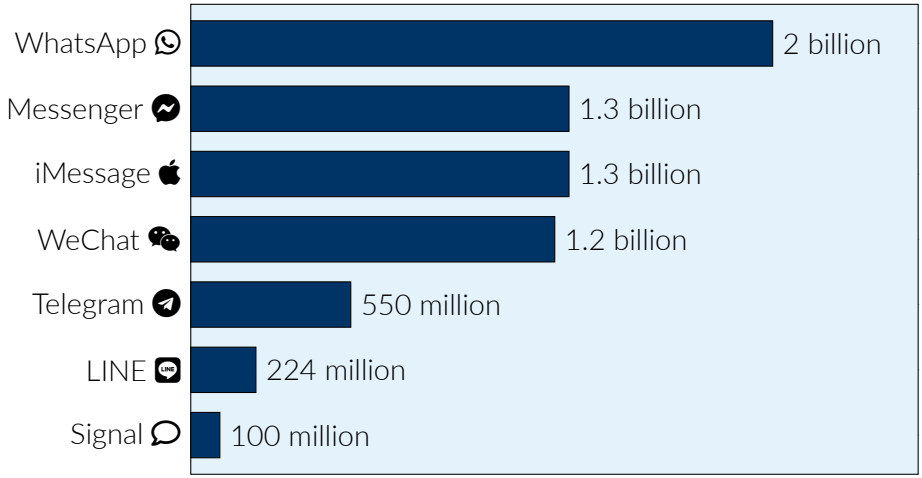
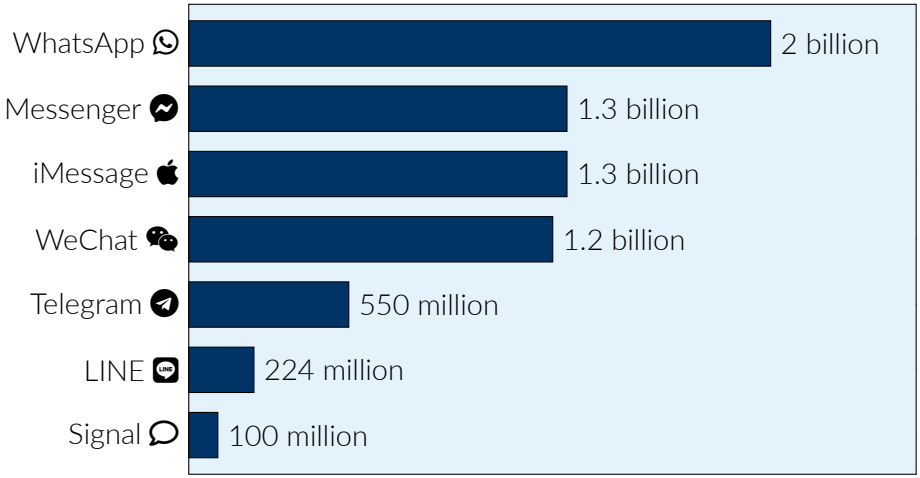
Messaging apps

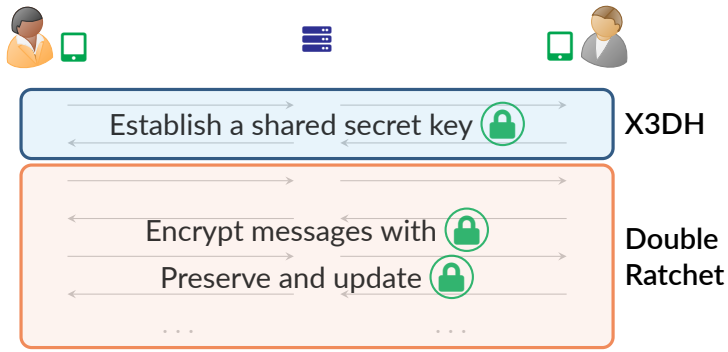


Messaging apps



Most of these apps use specific protocols.
We focus on variations of the Signal protocol (,,).

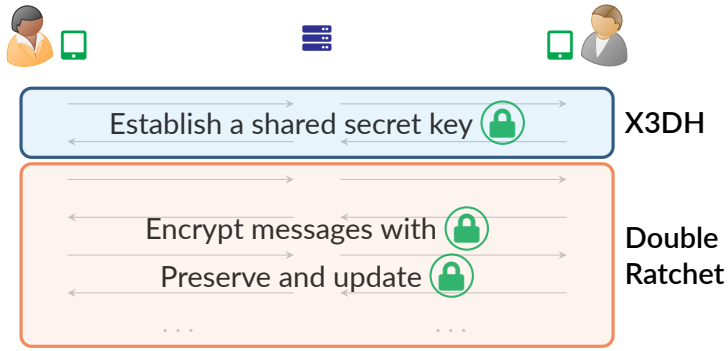
The Signal protocol



Two main threats

- Server compromise
- Device compromise

The Signal protocol

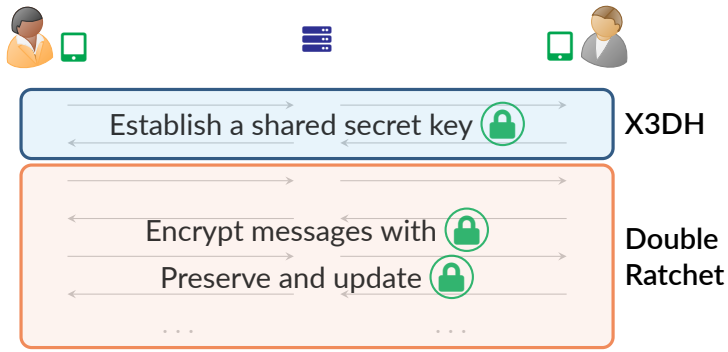


Pre-quantum world:

- **X3DH:**[1] Diffie-Hellman + XEdDSA + symmetric crypto (HKDF)
- **Double Ratchet:**[2] Diffie-Hellman + symmetric crypto (HKDF, HMAC, ...)

[1] https://signal.org/docs/specifications/x3dh/
[2] https://signal.org/docs/specifications/doubleratchet/

The Signal protocol



Post-quantum world:

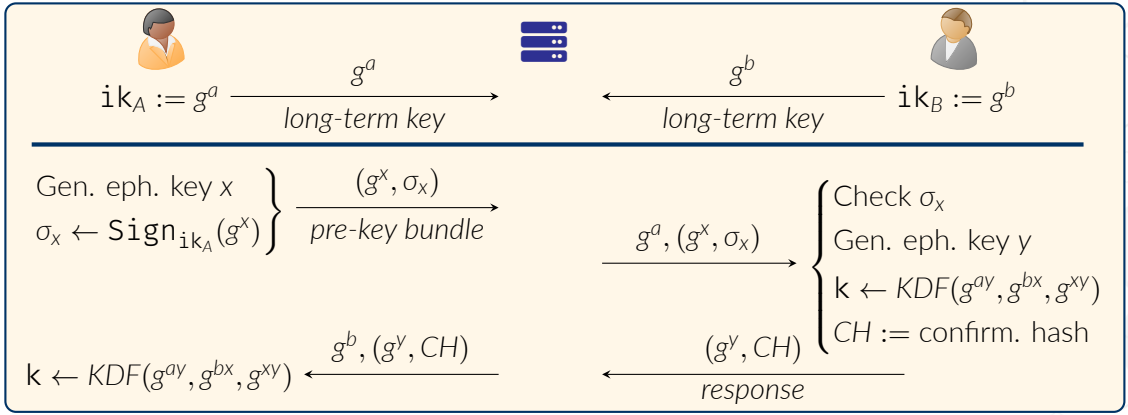
- **PQ X3DH:** KEM + (ring) signatures + symmetric crypto **[this work]**
- **PQ Double Ratchet:** KEM + symmetric crypto [ACD19]

Roadmap

1. Capture/formalize the properties expected from Signal's X3DH
2. Propose a generic construction that satisfies these properties

Understanding X3DH

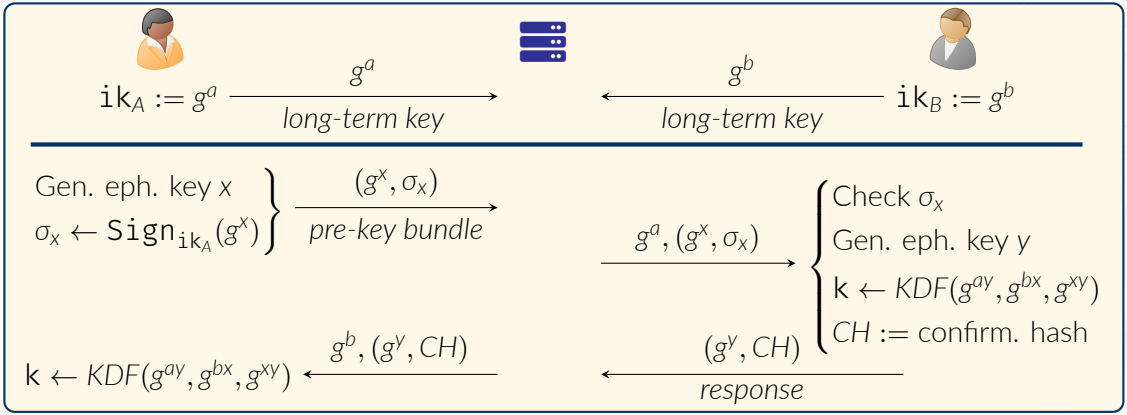
Reverse-engineering X3DH's spec [MP16]



Initial comments:

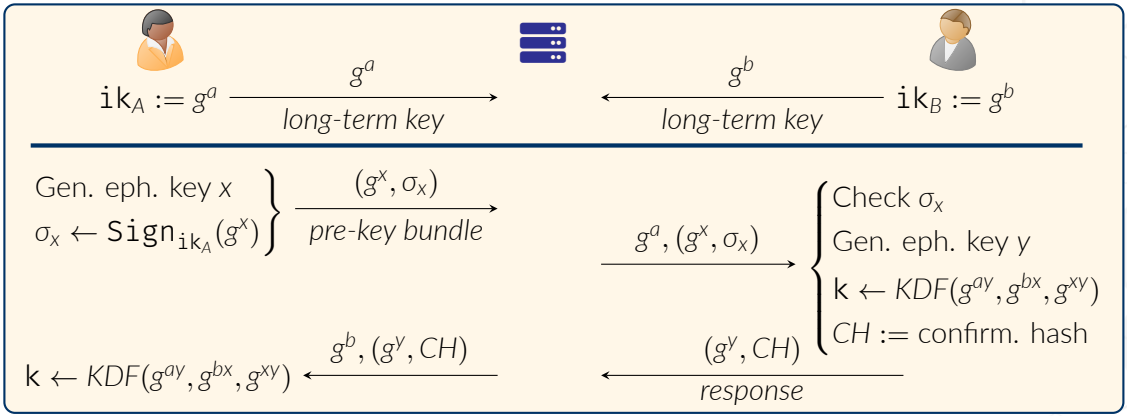
- Builds upon 3DH (same protocol without σ_x and CH).
- Note the two-message flow and the "*receiver-obliviousness*" of pre-key bundle.
- Parties delete ephemeral keys (x and y) as soon as they can (omitted in figure).

Authentication and forward secrecy



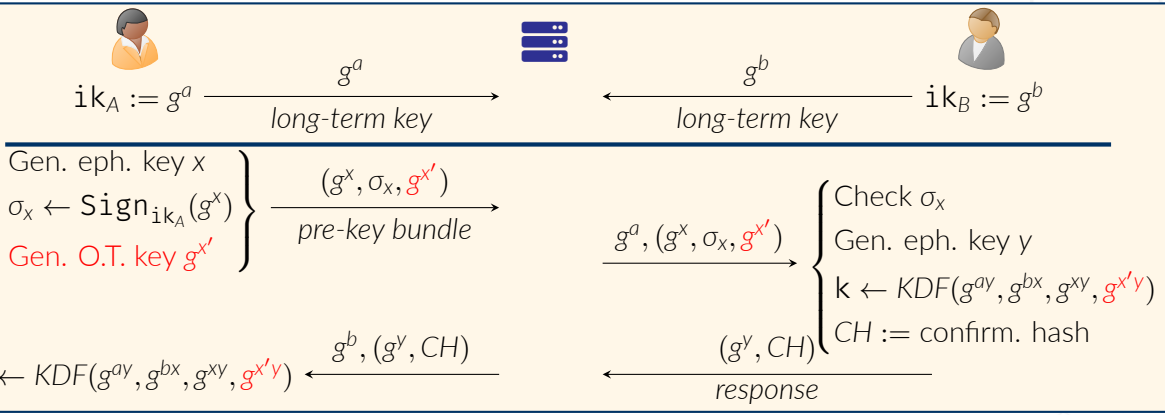
" Note that $[g^{ay}]$ and $[g^{bx}]$ provide mutual authentication, while $[g^{xy}$ provides] forward secrecy. "

Deniability



" X3DH doesn't give either Alice or Bob a publishable cryptographic proof of the contents of their communication or the fact that they communicated. "

One-time keys (optional)



X3DH allows to provide an optional one-time key.

- *Motivation:* (1) forward secrecy, and (2) protection against replay attacks
  - *Replay attacks:* there are simpler ways to thwart them
  - *Forward secrecy:* largely addressed by signed pre-keys and Double Ratchet

Wishlist

Functional properties:

- *Two-message flow:* Initiator → Responder → Initiator
- *Receiver-obliviousness:* first message is independent of the Responder[1]

Security properties:

- *Confidentiality:* session keys looks pseudorandom except for intended parties
- *Mutual authentication:* Initiator knows she talks to Responder, and reciprocally
  - Includes *Key-Compromise Impersonation* (KCI) attacks[2]
  - Includes *Unknown Key-Share* (UKS) attacks[3]
- *Deniability:* online/offline, against semi-honest/malicious adversaries

[1] Also known as *post-specified peers*.

[2] KCI: The adversary uses A's long-term key to impersonate other parties towards A.

[3] UKS: A and B compute the same key, but A believe he's talking to C.

Generic Constructions

Building blocks

Key establishment mechanism (KEM):

- $\mathtt{ek}$ = encapsulation key
- $\mathtt{dk}$ = decapsulation key
- $\mathtt{c}$, $\mathtt{k}$ = ciphertext, encapsulated key

- $\mathtt{Keygen}() \to (\mathtt{ek}, \mathtt{dk})$
- $\mathtt{Encaps}(\mathtt{ek}) \to (\mathtt{c}, \mathtt{k})$
- $\mathtt{Decaps}(\mathtt{dk}, \mathtt{c}) \to \mathtt{k}/\perp$

(Ring) signature scheme:

- $\mathtt{sk}$ = signing key
- $\mathtt{vk}$ = verification key
- σ = signature

- $\mathtt{Keygen}() \to (\mathtt{vk}, \mathtt{sk})$
- $\mathtt{Sign}_{\mathtt{sk}}(\mathtt{msg}) \to \sigma$
- $\mathtt{Verify}_{\mathtt{vk}}(\sigma, \mathtt{msg}) \to \top/\perp$

Pseudo-random function (PRF) $F_{\mathbf{k}}$.

V0: first generic construction

$\mathtt{lsk}_A := (\mathtt{sk}_A, \mathtt{dk}_A)$
$\mathtt{lpk}_A := (\mathtt{vk}_A, \mathtt{ek}_A)$

$\mathtt{lsk}_B := (\mathtt{sk}_B, \mathtt{dk}_B)$
$\mathtt{lpk}_B := (\mathtt{vk}_B, \mathtt{ek}_B)$

$(\mathtt{ek}_T, \mathtt{dk}_T) \leftarrow \mathsf{KEM.Keygen}()$
$\sigma_A \leftarrow \mathtt{Sign}_{\mathtt{sk}_A}(\mathtt{ek}_T)$

$\xrightarrow{\mathtt{lpk}_A, \mathtt{ek}_T, \sigma_A}$

$\mathtt{Verify}_{\mathtt{vk}_B}(\sigma_A, \mathtt{ek}_T)$
$(\mathtt{c}_A, \mathtt{k}_A) \leftarrow \mathtt{Encaps}(\mathtt{ek}_A)$
$(\mathtt{c}_T, \mathtt{k}_T) \leftarrow \mathtt{Encaps}(\mathtt{ek}_T)$
$\mathtt{k} \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$
$\sigma_B \leftarrow \mathtt{Sign}_{\mathtt{sk}_B}(\mathtt{sid})$

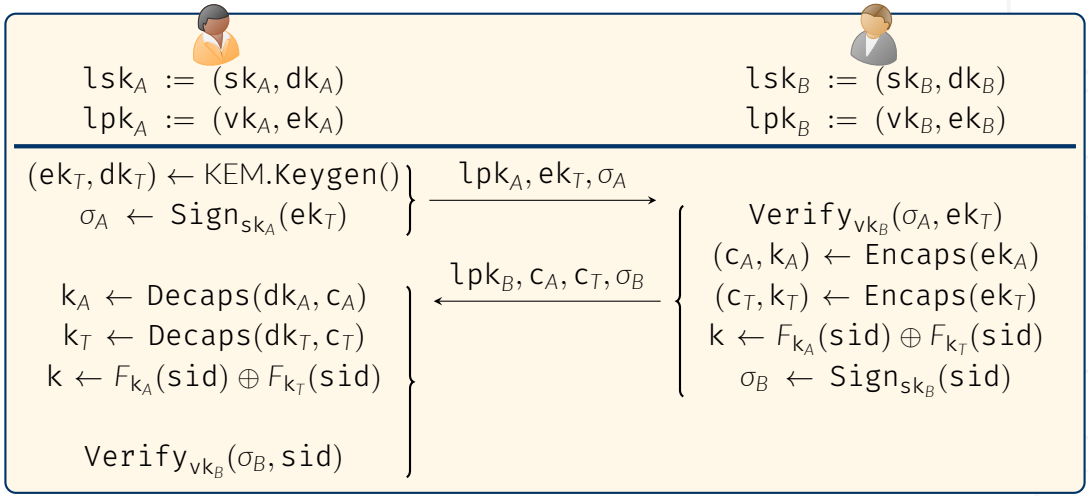
$\xleftarrow{\mathtt{lpk}_B, \mathtt{c}_A, \mathtt{c}_T, \sigma_B}$

$\mathtt{k}_A \leftarrow \mathtt{Decaps}(\mathtt{dk}_A, \mathtt{c}_A)$
$\mathtt{k}_T \leftarrow \mathtt{Decaps}(\mathtt{dk}_T, \mathtt{c}_T)$
$\mathtt{k} \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$

$\mathtt{Verify}_{\mathtt{vk}_B}(\sigma_B, \mathtt{sid})$

$\mathtt{sid} = (\mathtt{lpk}_A \| \mathtt{lpk}_B \| \mathtt{ek}_A \| \mathtt{c}_A \| \mathtt{c}_T)$ is the session identifier.

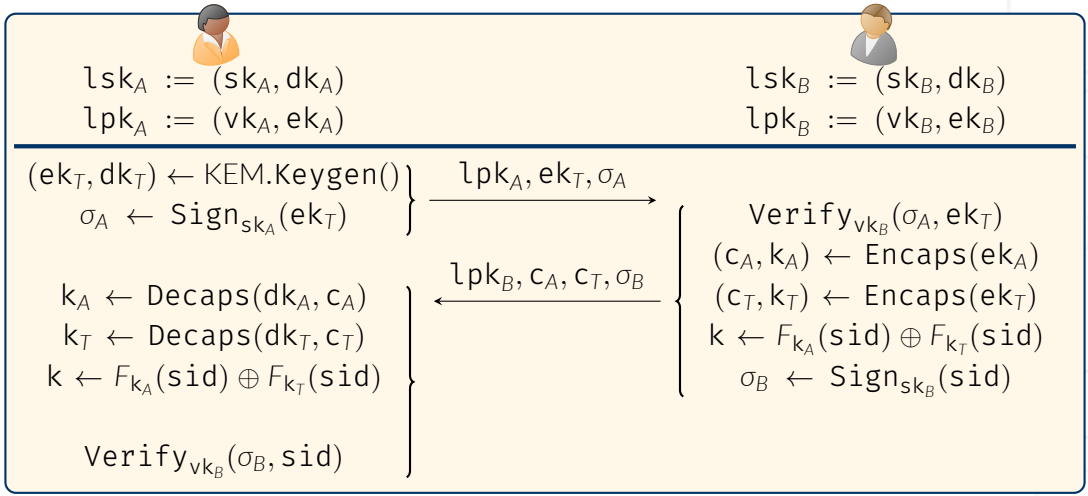
V0: first generic construction



Leakage:

- *Leakage of long-term keys:* secrecy of k is guaranteed by ek_T and c_T
- *State leakage (irrelevant for* *):* secrecy of k is guaranteed by c_A

V0: first generic construction



Mutual authentication:

- → is *explicitly* authenticated by σ_B.
- → is *implicitly* authenticated.

- → *KCI:* prevented by signatures σ_A and σ_B
- → *UKS:* prevented by $\mathtt{sid}$

V0: first generic construction

$\mathtt{lsk}_A := (\mathtt{sk}_A, \mathtt{dk}_A)$
$\mathtt{lpk}_A := (\mathtt{vk}_A, \mathtt{ek}_A)$

$\mathtt{lsk}_B := (\mathtt{sk}_B, \mathtt{dk}_B)$
$\mathtt{lpk}_B := (\mathtt{vk}_B, \mathtt{ek}_B)$

$(\mathtt{ek}_T, \mathtt{dk}_T) \leftarrow \mathsf{KEM.Keygen}()$
$\sigma_A \leftarrow \mathtt{Sign}_{\mathtt{sk}_A}(\mathtt{ek}_T)$

$\xrightarrow{\mathtt{lpk}_A, \mathtt{ek}_T, \sigma_A}$

$\mathtt{Verify}_{\mathtt{vk}_B}(\sigma_A, \mathtt{ek}_T)$
$(\mathtt{c}_A, \mathtt{k}_A) \leftarrow \mathtt{Encaps}(\mathtt{ek}_A)$
$(\mathtt{c}_T, \mathtt{k}_T) \leftarrow \mathtt{Encaps}(\mathtt{ek}_T)$
$\mathtt{k} \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$
$\sigma_B \leftarrow \mathtt{Sign}_{\mathtt{sk}_B}(\mathtt{sid})$

$\xleftarrow{\mathtt{lpk}_B, \mathtt{c}_A, \mathtt{c}_T, \sigma_B}$

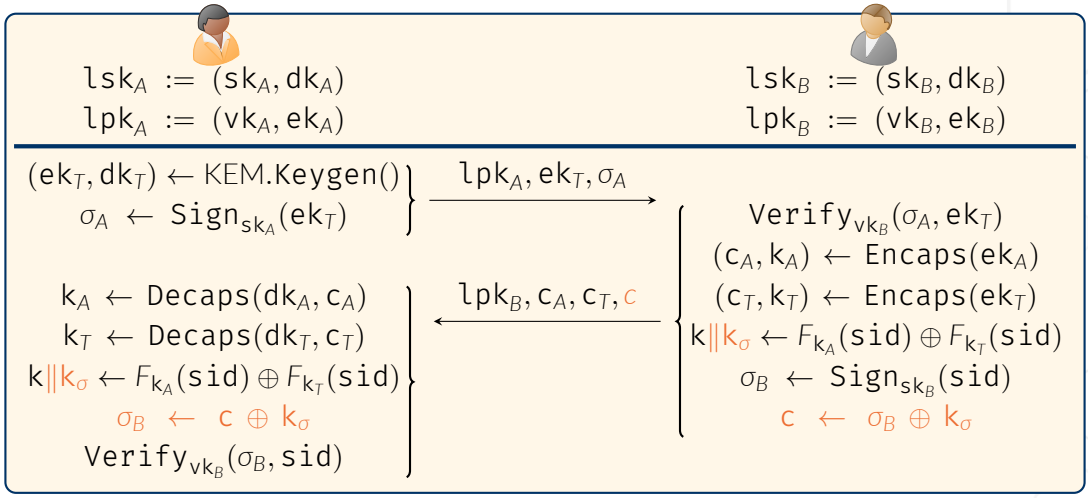
$\mathtt{k}_A \leftarrow \mathtt{Decaps}(\mathtt{dk}_A, \mathtt{c}_A)$
$\mathtt{k}_T \leftarrow \mathtt{Decaps}(\mathtt{dk}_T, \mathtt{c}_T)$
$\mathtt{k} \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$

$\mathtt{Verify}_{\mathtt{vk}_B}(\sigma_B, \mathtt{sid})$

Minor possible tweaks:

- *Omit* σ_A*:* Downgrades PFS to weak PFS (Double Ratchet then provides PFS again)
- *NAXOS trick:* mitigates leakage of 's randomness by combining it with $\mathtt{lsk}_B$

V1: very weakly deniable



We can tweak the protocol to achieve a weak flavour of deniability for free.

- We mask σ_B using a pseudorandom keystream derived from $\mathtt{k}_A, \mathtt{k}_T$ (tangerine).
- The transcript makes anonymous as long as doesn't cooperate.

V1.5: weakly deniable

$\mathtt{lsk}_A := (\mathtt{sk}_A, \mathtt{dk}_A)$
$\mathtt{lpk}_A := (\mathtt{vk}_A, \mathtt{ek}_A)$

$\mathtt{lsk}_B := (\mathtt{sk}_B, \mathtt{dk}_B)$
$\mathtt{lpk}_B := (\mathtt{vk}_B, \mathtt{ek}_B)$

$(\mathtt{ek}_T, \mathtt{dk}_T) \leftarrow \mathsf{KEM.Keygen}()$
$\sigma_A \leftarrow \mathtt{Sign}_{\mathtt{sk}_A}(\mathtt{ek}_T)$

$\mathtt{lpk}_A, \mathtt{ek}_T, \sigma_A$ →

$\mathtt{Verify}_{\mathtt{vk}_B}(\sigma_A, \mathtt{ek}_T)$
$(\mathtt{c}_A, \mathtt{k}_A) \leftarrow \mathsf{Encaps}(\mathtt{ek}_A)$
$(\mathtt{c}_T, \mathtt{k}_T) \leftarrow \mathsf{Encaps}(\mathtt{ek}_T)$
$\mathtt{k} \| \mathtt{k}_\sigma \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$
$\sigma_B \leftarrow \mathsf{RS.Sign}_{\mathtt{sk}_B, \mathtt{ring}}(\mathtt{sid})$
$\mathtt{c} \leftarrow \sigma_B \oplus \mathtt{k}_\sigma$

← $\mathtt{lpk}_B, \mathtt{c}_A, \mathtt{c}_T, \mathtt{c}$

$\mathtt{k}_A \leftarrow \mathsf{Decaps}(\mathtt{dk}_A, \mathtt{c}_A)$
$\mathtt{k}_T \leftarrow \mathsf{Decaps}(\mathtt{dk}_T, \mathtt{c}_T)$
$\mathtt{k} \| \mathtt{k}_\sigma \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$
$\sigma_B \leftarrow \mathtt{c} \oplus \mathtt{k}_\sigma$
$\mathsf{RS.Verify}_{\mathtt{ring}}(\sigma_B, \mathtt{sid})$

- Main idea: replace signatures by *ring* signatures (pine green).
- Setting $\mathtt{ring} = \{\mathtt{vk}_A, \mathtt{vk}_B\}$ only gives a weak flavour of deniability.

V2: deniable (offline, semi-honest)

$\mathtt{lsk}_A := (\mathtt{sk}_A, \mathtt{dk}_A)$
$\mathtt{lpk}_A := (\mathtt{vk}_A, \mathtt{ek}_A)$

$\mathtt{lsk}_B := (\mathtt{sk}_B, \mathtt{dk}_B)$
$\mathtt{lpk}_B := (\mathtt{vk}_B, \mathtt{ek}_B)$

$(\mathtt{ek}_T, \mathtt{dk}_T) \leftarrow \mathsf{KEM.Keygen}()$
$\sigma_A \leftarrow \mathtt{Sign}_{\mathtt{sk}_A}(\mathtt{ek}_T)$
$(\mathtt{sk}_T, \mathtt{vk}_T) \leftarrow \mathsf{RS.Keygen}()$

$\xrightarrow{\mathtt{lpk}_A, \mathtt{ek}_T, \sigma_A, \mathtt{vk}_T}$

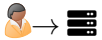
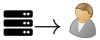
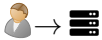
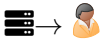
$\mathtt{Verify}_{\mathtt{vk}_B}(\sigma_A, \mathtt{ek}_T)$
$(\mathtt{c}_A, \mathtt{k}_A) \leftarrow \mathtt{Encaps}(\mathtt{ek}_A)$
$(\mathtt{c}_T, \mathtt{k}_T) \leftarrow \mathtt{Encaps}(\mathtt{ek}_T)$
$\mathtt{k} \| \mathtt{k}_\sigma \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$
$\sigma_B \leftarrow \mathsf{RS.Sign}_{\mathtt{sk}_B, \mathtt{ring}}(\mathtt{sid})$
$\mathtt{c} \leftarrow \sigma_B \oplus \mathtt{k}_\sigma$

$\xleftarrow{\mathtt{lpk}_B, \mathtt{c}_A, \mathtt{c}_T, \mathtt{c}}$

$\mathtt{k}_A \leftarrow \mathtt{Decaps}(\mathtt{dk}_A, \mathtt{c}_A)$
$\mathtt{k}_T \leftarrow \mathtt{Decaps}(\mathtt{dk}_T, \mathtt{c}_T)$
$\mathtt{k} \| \mathtt{k}_\sigma \leftarrow F_{\mathtt{k}_A}(\mathtt{sid}) \oplus F_{\mathtt{k}_T}(\mathtt{sid})$
$\sigma_B \leftarrow \mathtt{c} \oplus \mathtt{k}_\sigma$
$\mathsf{RS.Verify}_{\mathtt{ring}}(\sigma_B, \mathtt{sid})$

- Main idea: replace signatures by *ring* signatures (pine green).
- Setting $\mathtt{ring} = \{\mathtt{vk}_A, \mathtt{vk}_B\}$ only gives a weak flavour of deniability.
- Setting $\mathtt{ring} = \{\mathtt{vk}_T, \mathtt{vk}_B\}$ with $\mathtt{vk}_T$ an ephemeral key makes (V2) truly deniable.

Bandwidth cost of V1 in bytes

Scheme	`lpk`				
Kyber512 + Falcon512	1697	1490	3187	2226	3923
Kyber512 + Dilithium2	2112	3220	5332	3956	6068
Kyber512 + SPHINCS$^+$	832	17888	18720	18624	19456

Conclusion and Further Reading

Further reading:

- Full paper
  https://ia.cr/2021/616
- Keitaro's presentation at PKC 2021 (video)
  https://www.youtube.com/watch?v=VO4fw0UHdMI
- Keitaro's presentation at PKC 2021 (slides)
  https://kaminomisosiru.github.io/assets/pdf/HKKP-PKC2021.pdf
- C implementation by Kris:
  https://github.com/post-quantum-cryptography/post-quantum-state-leakage-secure-ake

Related works:

- PQ X3DH:
  - Generic [BFG+22]
  - SIDH-based [DG21]
- PQ Double Ratchet
  - Generic [ACD19]

Questions?

https://ia.cr/2021/616

Joël Alwen, Sandro Coretti, and Yevgeniy Dodis.
The double ratchet: Security notions, proofs, and modularization for the Signal protocol.
In Yuval Ishai and Vincent Rijmen, editors, *EUROCRYPT 2019, Part I*, volume 11476 of *LNCS*, pages 129–158. Springer, Heidelberg, May 2019.

Jacqueline Brendel, Rune Fiedler, Felix Günther, Christian Janson, and Douglas Stebila.
Post-quantum asynchronous deniable key exchange and the signal handshake.
In Goichiro Hanaoka, Junji Shikata, and Yohei Watanabe, editors, *Public-Key Cryptography – PKC 2022*, pages 3–34, Cham, 2022. Springer International Publishing.

Samuel Dobson and Steven D. Galbraith.
Post-quantum signal key agreement with SIDH.
Cryptology ePrint Archive, Report 2021/1187, 2021.
https://eprint.iacr.org/2021/1187.

Moxie Marlinspike and Trevor Perrin.
The x3dh key agreement protocol, November 2016.
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