Careful with MAc-then-SIGn: A Computational Analysis of the EDHOC Lightweight Authenticated Key Exchange Protocol

Felix Günther and **Marc Ilunga**

March 27, 2023

Proliferation of low-powered devices

Image by Moritz Kindler

- Limited computing power
- Bandwidth constraints
- Plagued by vulnerabilities[1]

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- EDHOC: a proposal by the IETF LAKE WG.
- Use case: OSCORE[1] protocol (secure transport)
- 4 mutual authentication methods (static DH and/or Signature)
  - This talk: SIG-SIG
  - Design similar to TLS1.3 and based on SIGMA[2]

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TLS 1.3 is a secure authenticated key exchange protocol

- Q: Why not simply use TLS 1.3?
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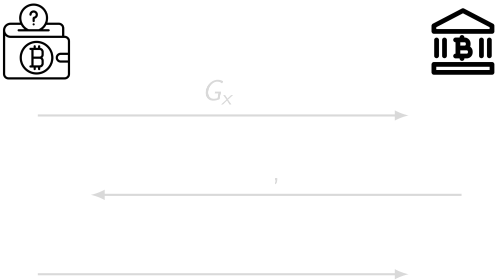
(D)TLS 1.3 is not lightweight: up to 7x bandwidth usage

	Total protocol size (bytes)[1]
DTLS 1.3 (ECDHE)	880
TLS 1.3 (ECDHE)	789
EDHOC (STAT-STAT)	101

[1] **empty citation**.

EDHOC in SIG-SIG Mode: An AKE based on Diffie-Hellman



Initiator (1)

$x \xleftarrow{\$} \mathbb{Z}_q;\ G_x \leftarrow xG$

Responder(1)

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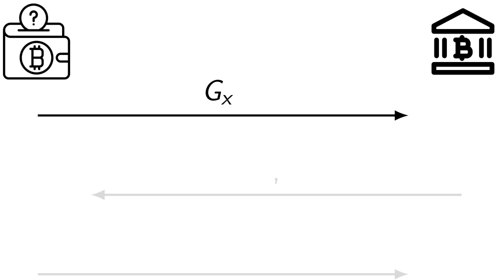

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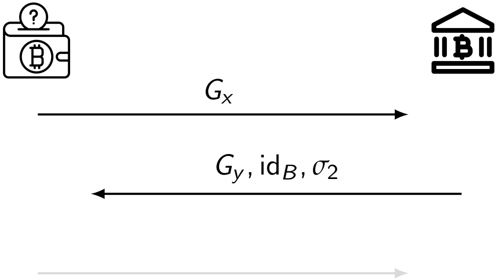

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$\sigma_2 \leftarrow \mathrm{Sign}(sk_R, \tau_2 \dots)$

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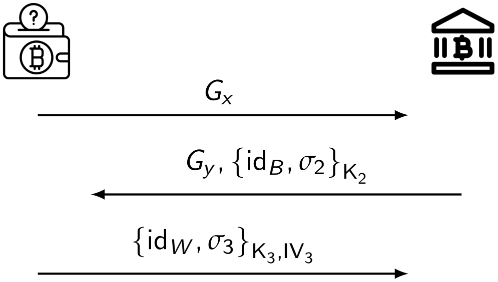
EDHOC in SIG-SIG Mode: An AKE with identity protection



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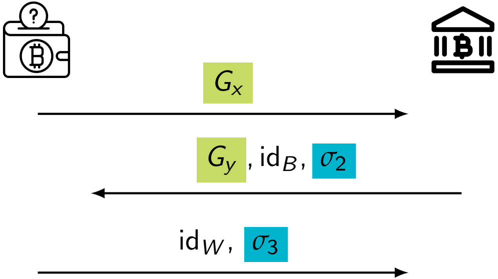
EDHOC in SIG-SIG Mode: An AKE $\approx$ SIGMA



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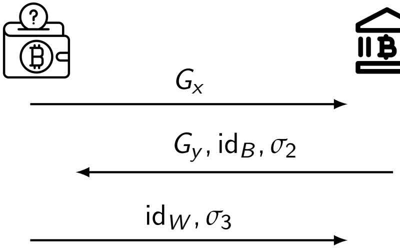
EDHOC SIG-SIG ≈ SIGMA: MAC "under" signature



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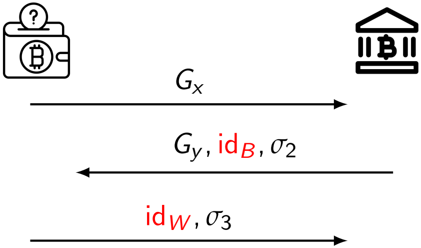
EDHOC SIG-SIG ≈ SIGMA: Abbreviated identities



- id_X Short credential identifier for X
- size $\ll$ X.509 Cert
- need not be unique[1]

  applications MUST NOT assume that 'kid' values are unique and several keys associated with a 'kid' may need to be checked [by the recipient] before the correct one is found.

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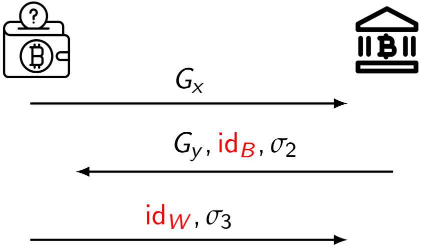

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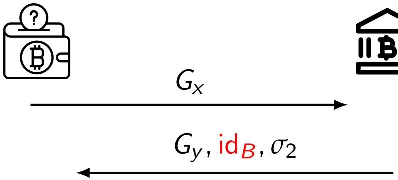
[1] Selander, Mattsson, and Palombini, *Ephemeral Diffie-Hellman Over COSE (EDHOC) – draft-ietf-lake-edhoc-17*, Section 3.5.3.

Abbreviated identifiers introduce new challenges



RunInit2

$\ldots$

foreach (U, pk_U) **with** $\mathsf{id}_U = \mathsf{id}_B$:

  $\tau_2 \leftarrow \mathsf{MAC}(\mathsf{id}_U, \ldots)$

  if $\mathsf{Sig.Vf}(pk_U, \tau_2 \ldots, \sigma_2) = 1$:

    $\mathsf{pid} \leftarrow U$; **endforeach**

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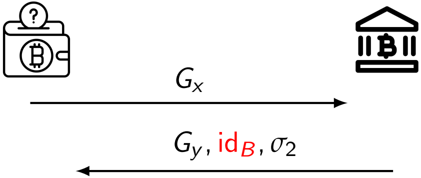

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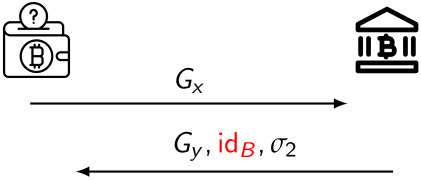

What if an attacker also uses id_B?

Duplicate Signature Key Selection attacks.

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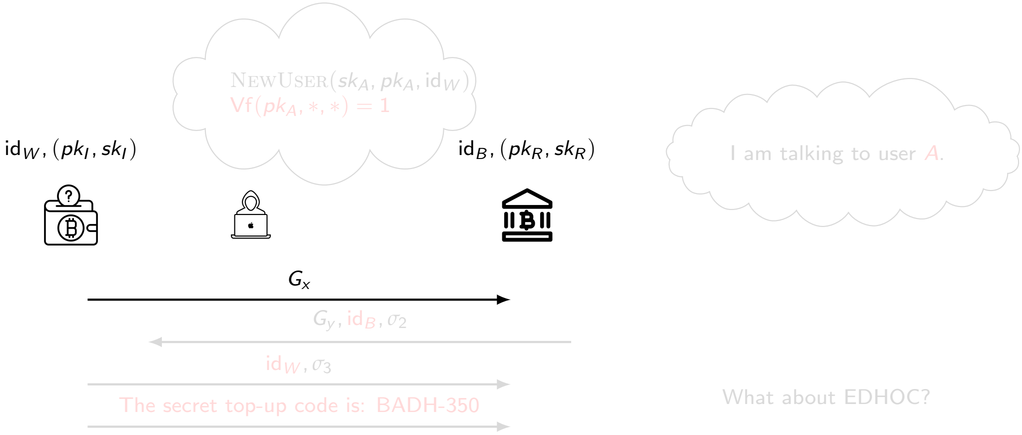

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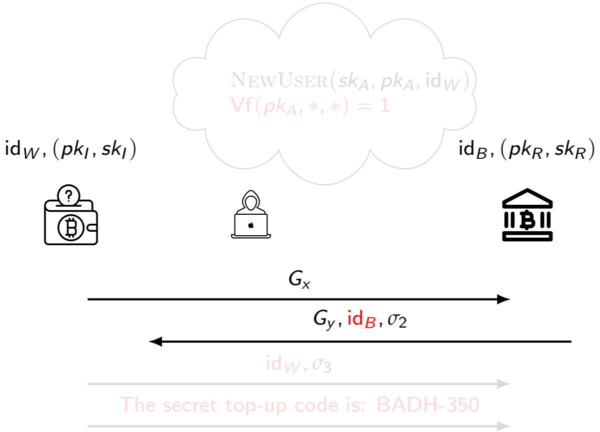

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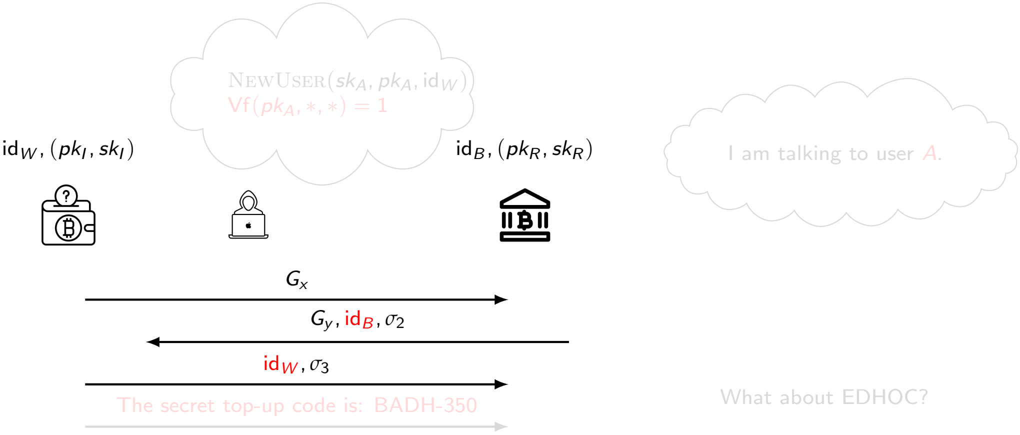

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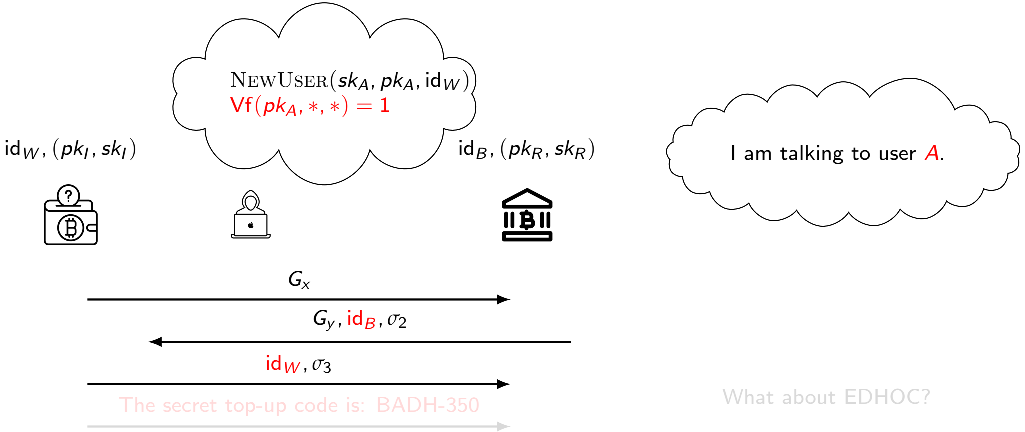

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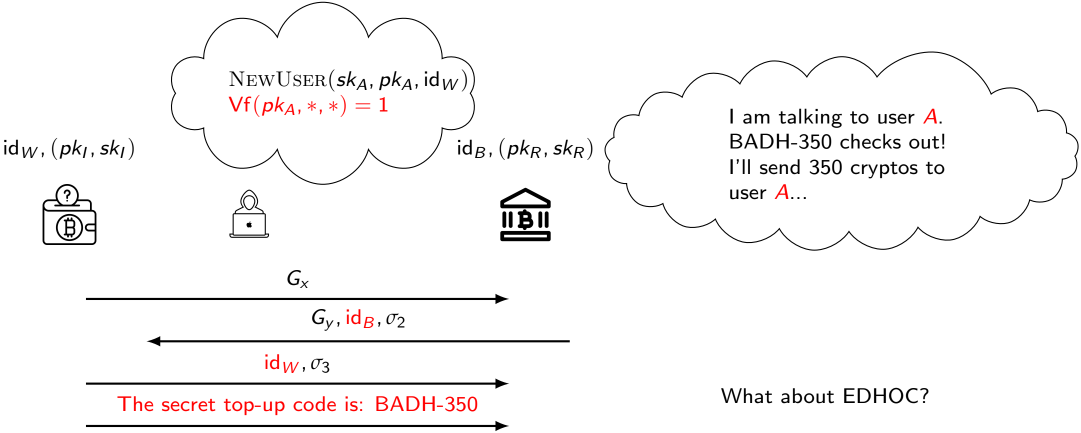

What about EDHOC?

EDHOC provides strong authentication guarantees even under colliding identifiers

- Assuming universal exclusive ownership[1] of the signature schemes
- S-UEO for signature scheme Σ (informal):
  - Key pair: $(pk, sk) \xleftarrow{\$} \Sigma.\mathsf{KGen}()$
  - Adversary $\mathcal{A}$ obtains $set(m_i, \sigma_i)$ (produced by sk)
  - Goal of $\mathcal{A}$: Produce (pk^*, m^*) s.t $\mathsf{Vf}(pk^*, m^*, \sigma_j) = 1$ and $pk \neq pk^*$
  - S-UEO $\implies$ $\mathcal{A}$ cannot succeed.

[1] Pornin and Stern, "Digital Signatures Do Not Guarantee Exclusive Ownership".

Security Model: Multi-Stage Key Exchange Model

$\mathbf{G}_{MSKE}$

$$\mathcal{O}\text{racles} = \left\{ \begin{array}{l} \textsc{Send} \\ \textsc{NewSession} \\ \textsc{RevLongTermKey} \\ \textsc{RevSessionKey} \\ \textsc{NewUser}^{1}(sk, pk, \mathrm{id}) \end{array} \right\}$$

$\mathcal{A}$

[1] Boyd et al., "ASICS: Authenticated Key Exchange Security Incorporating Certification Systems".

MSKE: Security goals

- Key indistinguishability
- Forward security
- Explicit authentication: When a session accepts with an authenticated peer, there is indeed a corresponding session of that peer.

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Let $\mathcal{A}$ be an MSKE adversary. For at most n_U users and n_S sessions, there exists adversaries $\mathcal{B}_j$ such that:

$$
\begin{aligned}
\mathrm{Adv}^{\mathrm{MSKE}}_{\mathcal{A}}(\text{EDHOC-Sig-Sig}) \leq \frac{{n_S}^2}{q} + \\
\mathrm{Adv}^{\mathrm{CR}}_{\mathcal{B}_4}(\mathsf{H}) + \\
4n_S \left(\begin{array}{r} n_U \cdot \mathrm{Adv}^{\mathrm{SUF\text{-}CMA}}_{\mathcal{B}_{I.2}}(\mathsf{Sig}) + \\ \mathrm{Adv}^{\mathrm{S\text{-}UEO}}_{\mathcal{B}_{I.4}}(\mathsf{Sig}) \end{array} \right) + \\
4n_S \left(\begin{array}{r} n_U \cdot \mathrm{Adv}^{\mathrm{EUF\text{-}CMA}}_{\mathcal{B}_{II.A2}}(\mathsf{Sig}) + \\ \mathrm{Adv}^{\mathrm{snPRF\text{-}ODH}}_{\mathcal{B}_{II.B2}}(\mathsf{Extract}) + \\ \mathrm{Adv}^{\mathrm{PRF}}_{\mathcal{B}_{II.B3}}(\mathsf{Expand}) \end{array} \right)
\end{aligned}
$$

Assumption	scheme	
Collision resistance	SHA2, Shake128	✓
SUF-CMA	Ed25519	✓
	ECDSA	✗
S-UEO	Ed25519	✓
	ECDSA	✗
EUF-CMA	Ed25519	✓
	ECDSA	✓
PRF-ODH	HKDF.Extract	✓
	KMAC	(?)
PRF	HKDF.Expand	✓
	KMAC	✓

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PRF	HKDF.Expand	✓
	KMAC	✓

ECDSA might be fine for EDHOC

- S-UEO ✗: EDHOC includes the pub key alongside messages to be signed (✓)
- SUF-CMA ✗: Implementations could use “canonical” signatures (✓ ?).

Positive collaboration with the LAKE working group

- Numerous contributions to EDHOC by several parties
  - Jacomme et al.: Full symbolic analysis of latest draft[1]
  - Cottier & Pointcheval: Computation analysis of STAT-STAT[2]
  - Norman et al.: Early symbolic analysis[3]
- Reminiscent of development of TLS 1.3

[1] Jacomme et al., "A comprehensive, formal and automated analysis of the EDHOC protocol".

[2] Cottier and Pointcheval, *Security Analysis of the EDHOC protocol*.

[3] Norrman, Sundararajan, and Bruni, "Formal Analysis of EDHOC Key Establishment for Constrained IoT Devices".

Chasing a moving target

- Worked through drafts (12-17)
- In an ideal world: tooling for automated proofs

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Contributions overview: Insights from our computational analysis

- Dedicated session key (PRK_{out}) added in draft 14 (with Jacomme et al.[1])
- Full credentials in transcript hashes in key derivation.
- Transcript hashes from plaintext instead of ciphertexts
- Key separation in key derivation

[1] Jacomme et al., "A comprehensive, formal and automated analysis of the EDHOC protocol".

Conclusion

- EDHOC is a LAKE for constrained environments with new security challenges
- Our contributions:
  - Strong security model for the LAKE setting
  - Security analysis and proof that EDHOC(SIG-SIG) is a secure LAKE in a strong adversarial model
  - Design contributions to EDHOC
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See EuroS&P 2023 Paper

(eprint `ia.cr/2022/1705`)

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