The 5G-AKA Authentication Protocol Privacy

Adrien Koutsos
LVS, ENS Paris-Saclay

January 18, 2019

The Authentication and Key Agreement Protocol

The Protocol

AKA is a key exchange protocol between:

- The user equipment (UE): the mobile phone.
- The serving network (SN): the antenna.
- The home network (HN): the service provider (Free, Orange, SFR ...)

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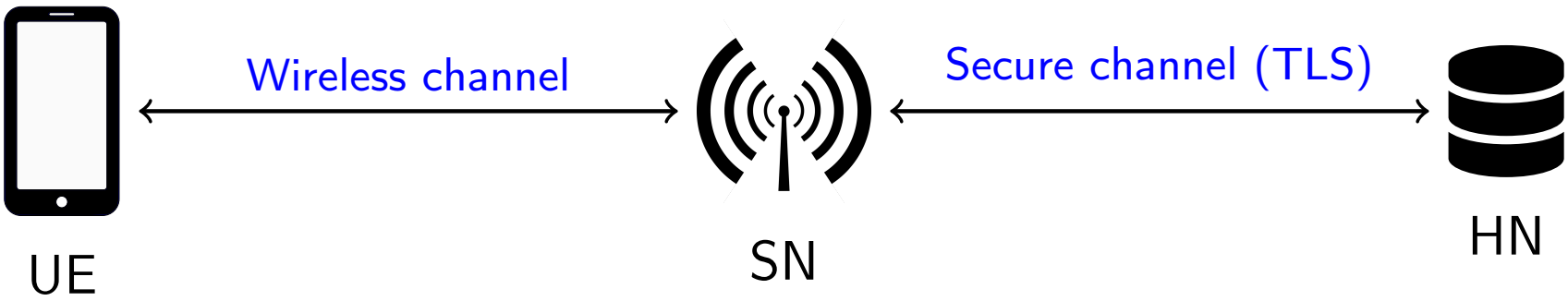

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- Authentication of the antenna by the network.
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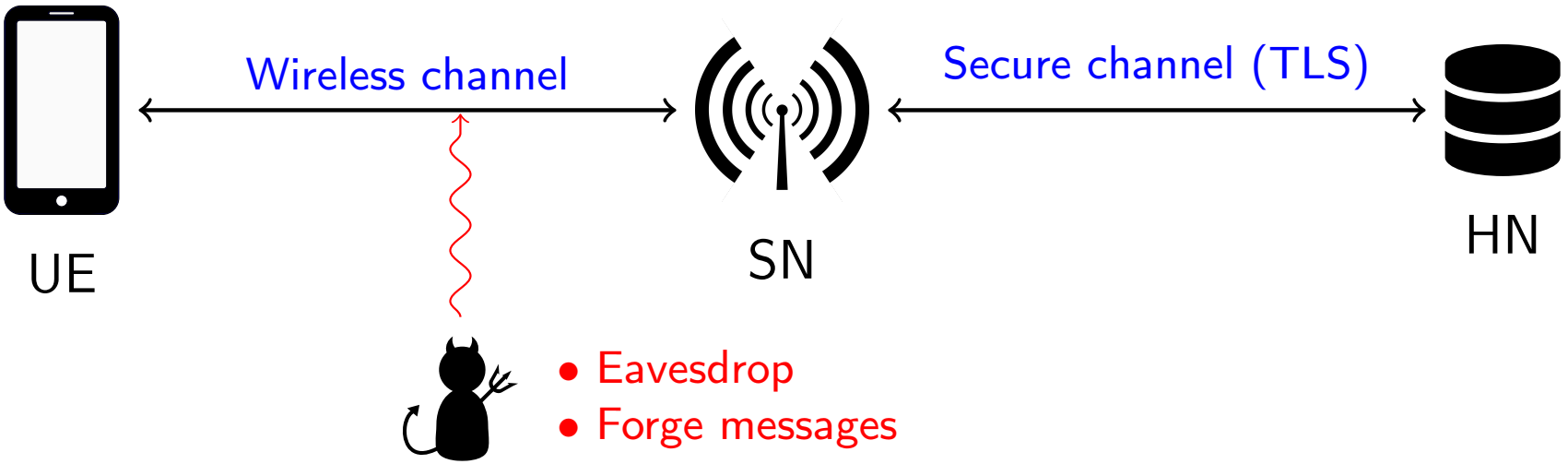

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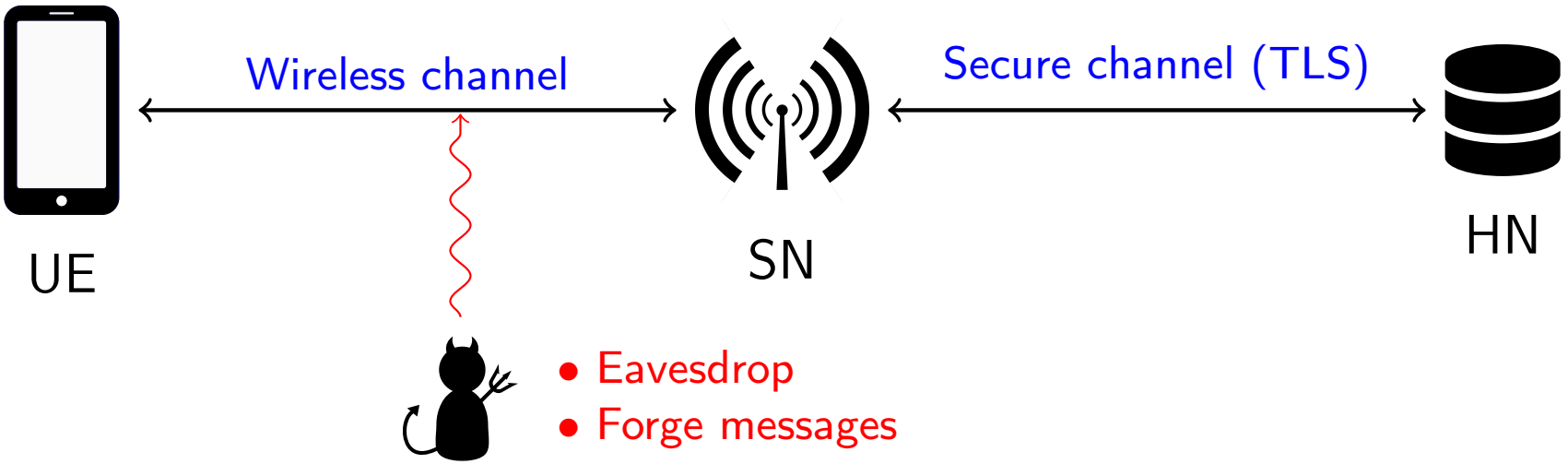

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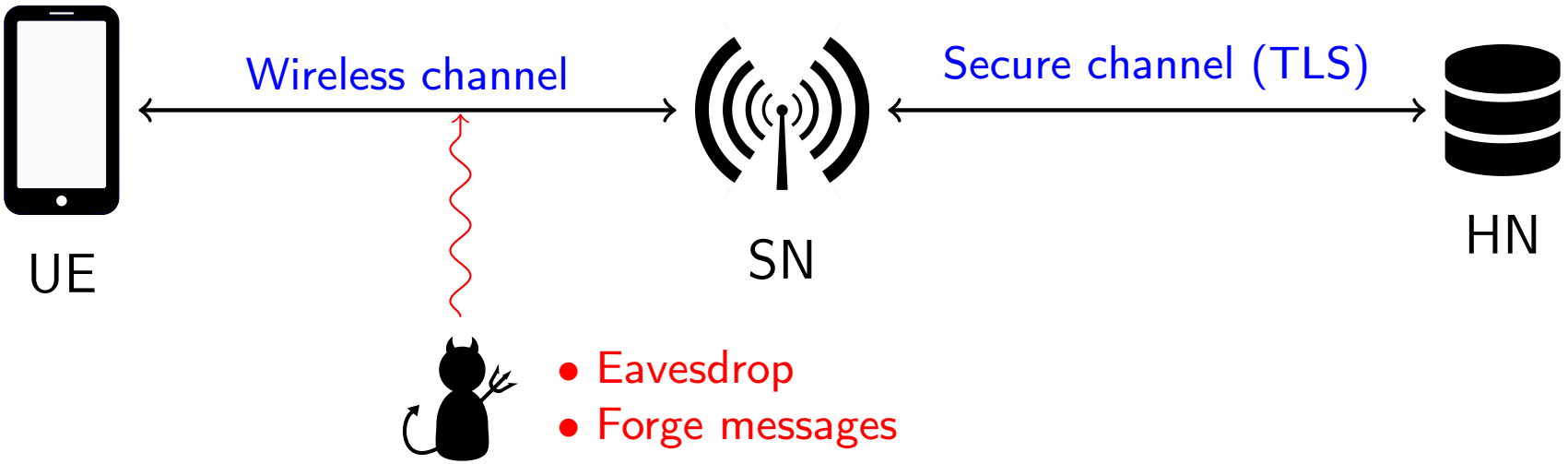

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$\Longrightarrow$ We do not model the antenna: we have a two party protocol.

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Cryptographic Primitives

- Asymmetric encryption requires randomness.

$\Rightarrow$ 4G-AKA uses only symmetric one-way functions.

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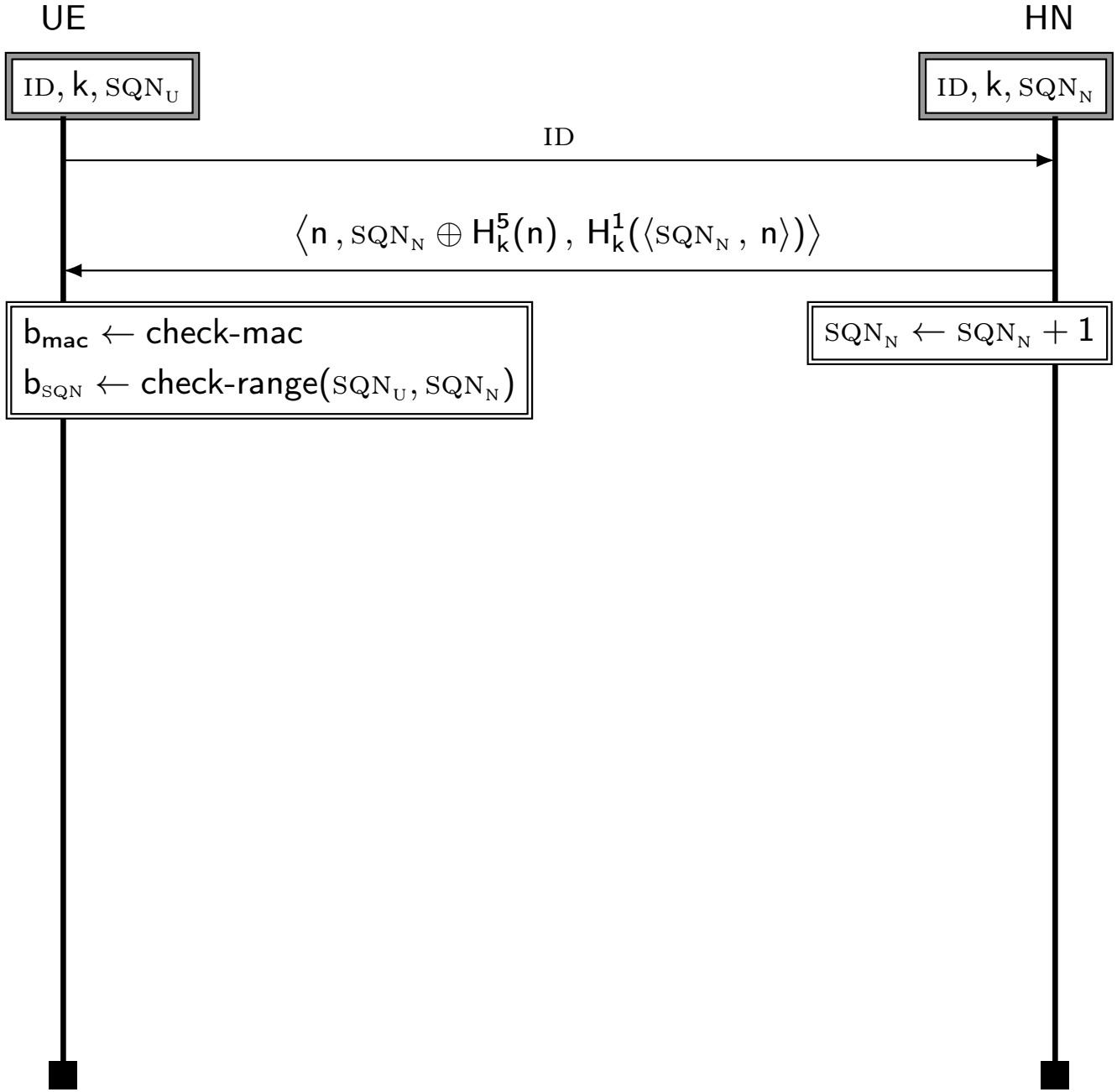
Authentication protocols need to prevent message replays. In 4G-AKA:

- The antenna uses a random challenge.
- The mobile phone uses a sequence number SQN:
  - Incremented after each successful session.
  - Tracked by the user and the antenna ($\mathrm{SQN_U}$ and $\mathrm{SQN_N}$).

  $\Rightarrow$ De-synchronization possible.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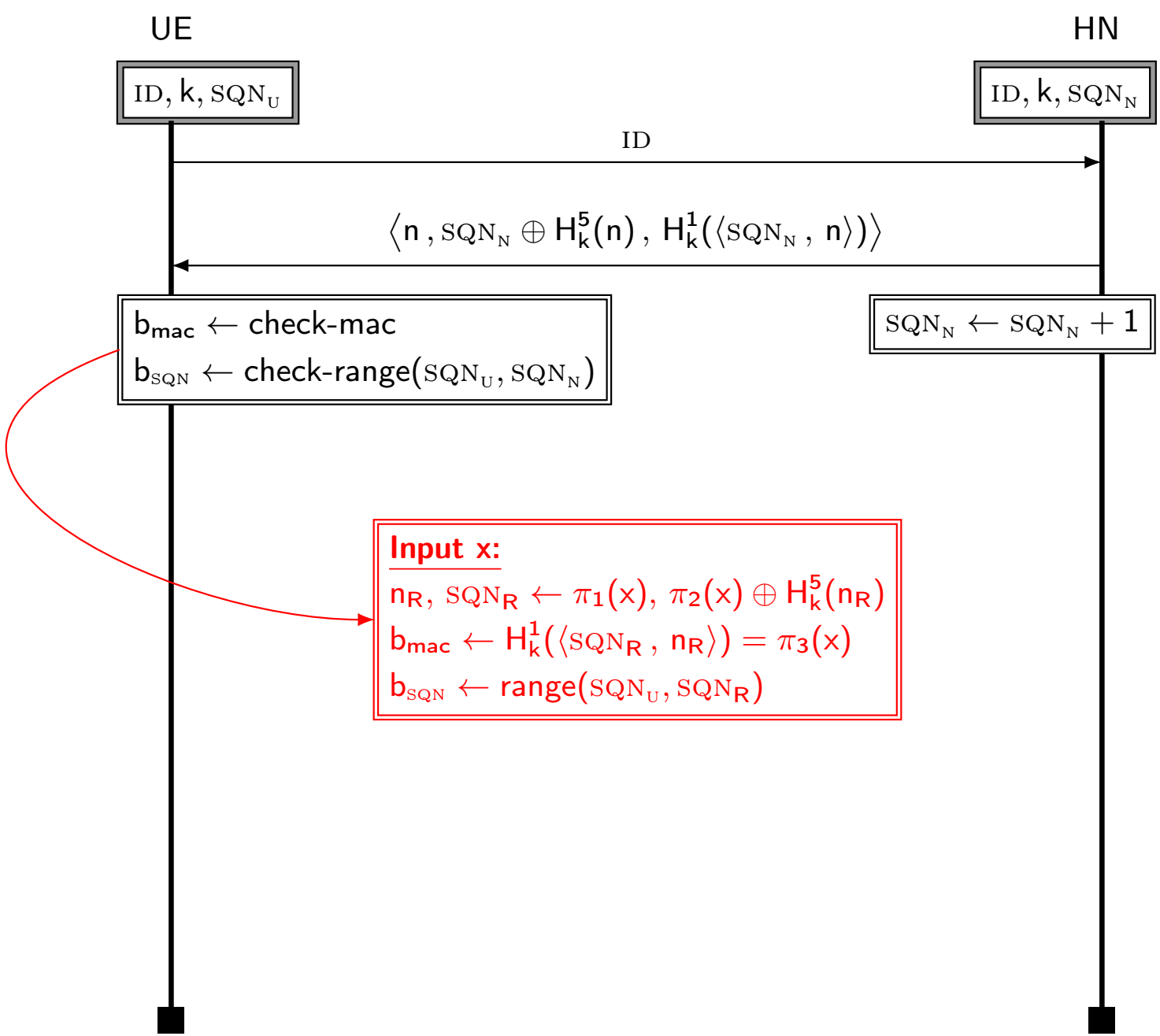
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Input x:
$\mathsf{n_R}, \mathrm{SQN_R} \leftarrow \pi_1(\mathsf{x}), \pi_2(\mathsf{x}) \oplus \mathsf{H}^5_{\mathsf{k}}(\mathsf{n_R})$
$\mathsf{b_{mac}} \leftarrow \mathsf{H}^1_{\mathsf{k}}(\langle \mathrm{SQN_R}\,, \mathsf{n_R}\rangle) = \pi_3(\mathsf{x})$
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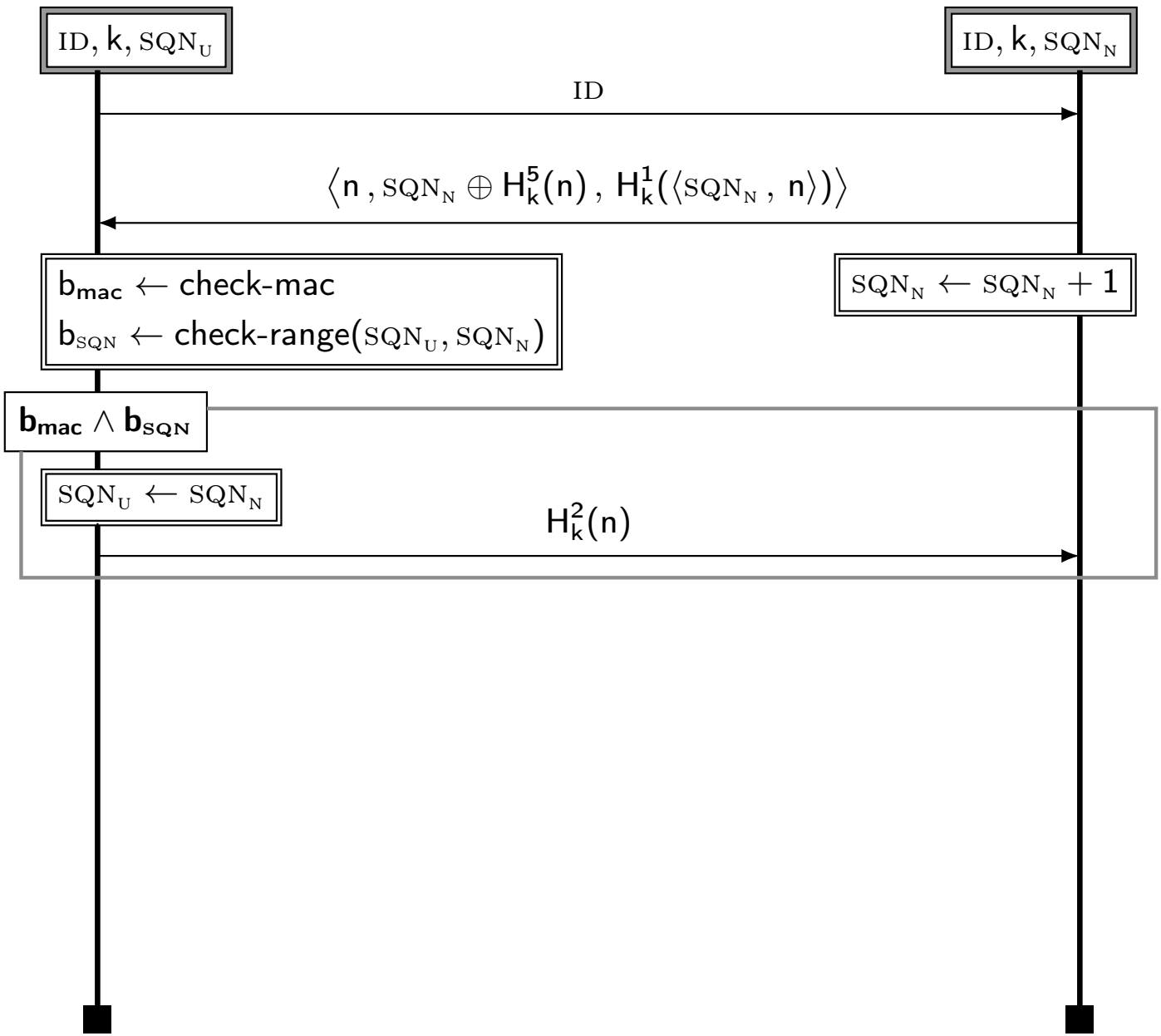
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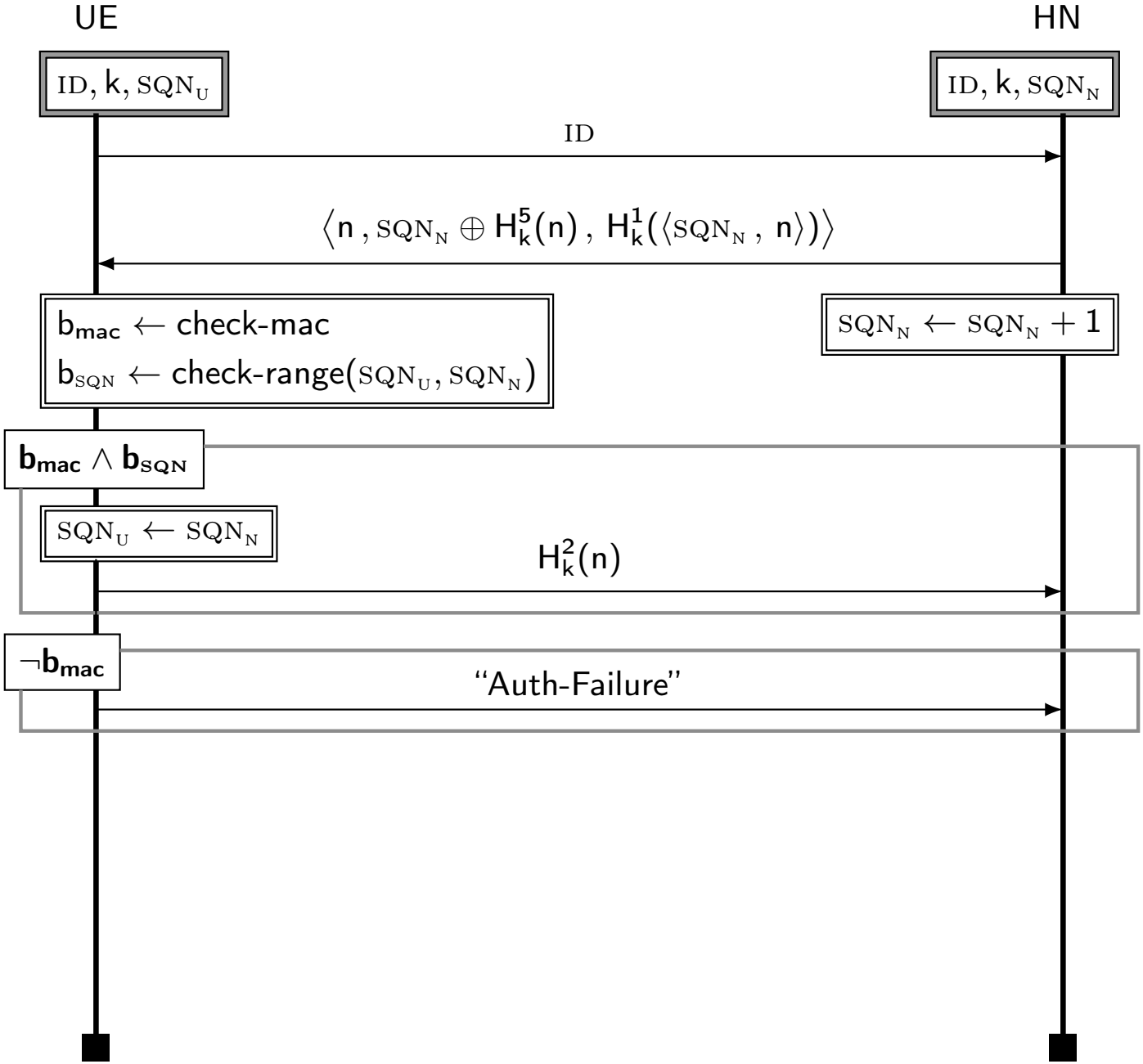
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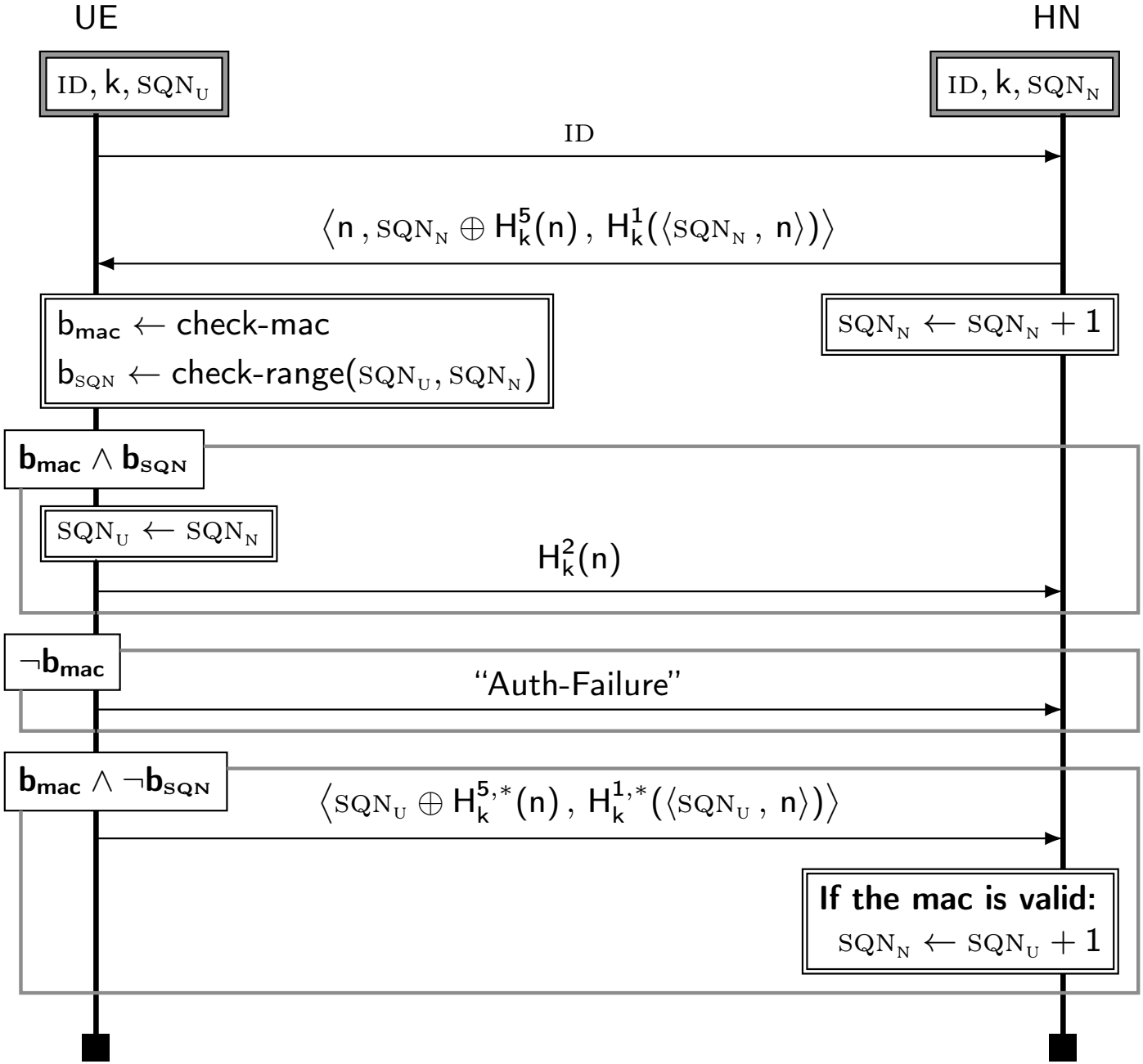
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Privacy in 4G-AKA

Not confidentiality of the user identity

The ID is sent in plain text!

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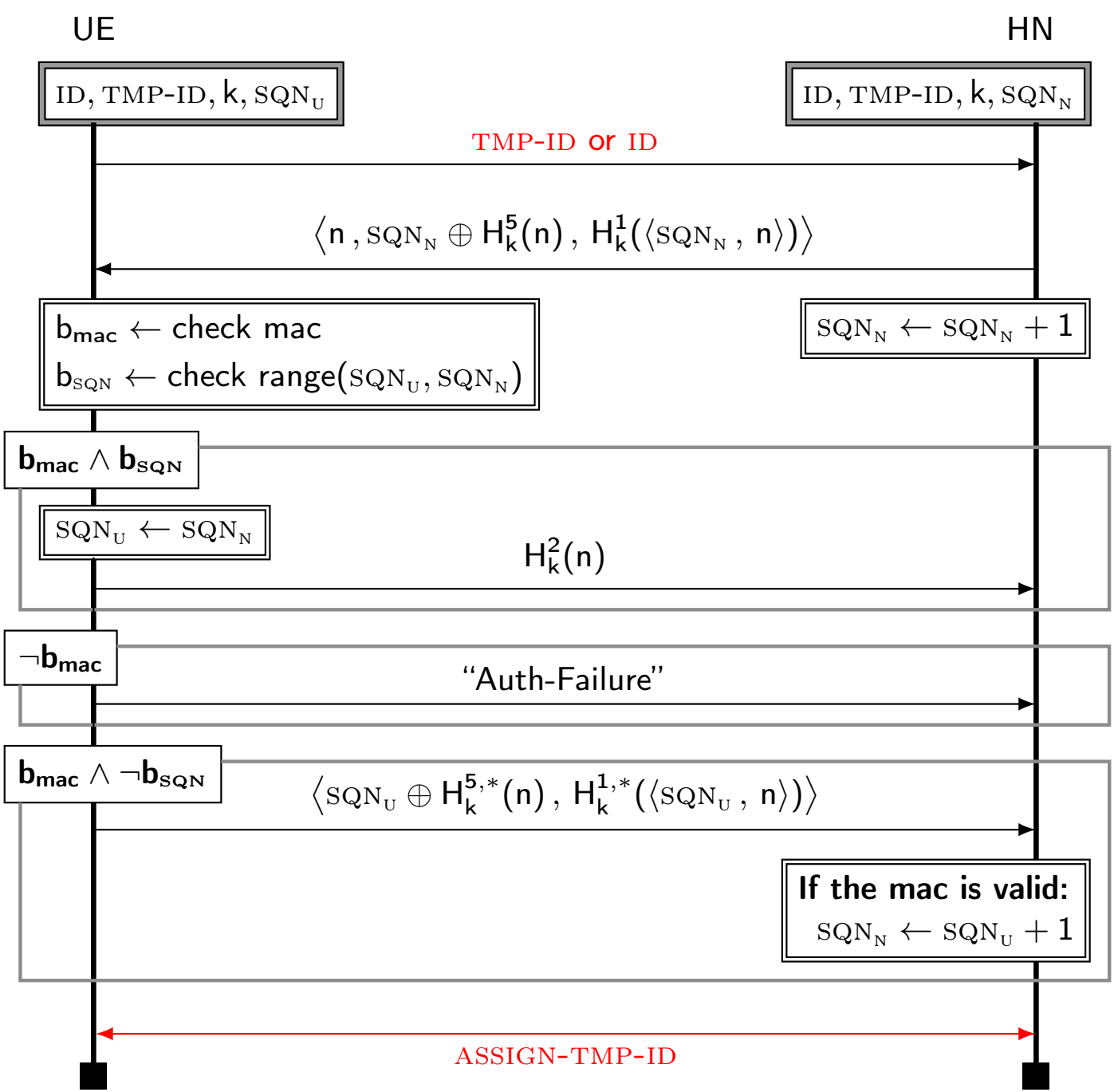
4G-AKA solution

Use a temporary identity TMP-ID instead of the permanent identity ID:

- The network has a mapping from TMP-IDs to IDs.
- Each TMP-ID should be used at most once.
- The network assigns new TMP-ID after each successful session.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Once a temporary identity is set up, the ID is protected if:

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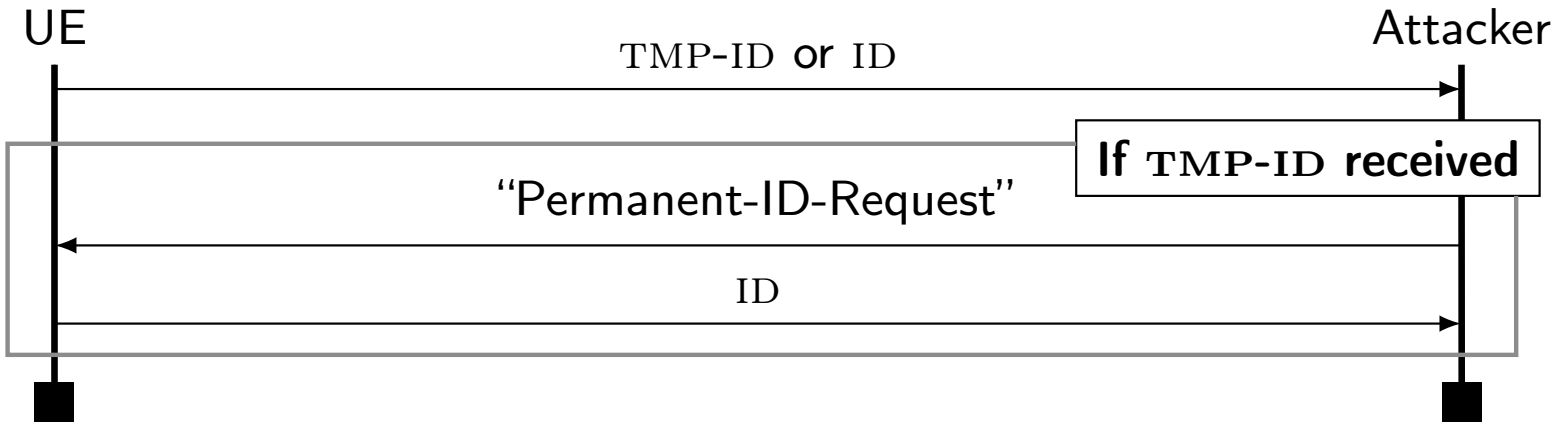
$\Longrightarrow$ This is not realistic!

The IMSI Catcher Attack [Strobel, 2007]



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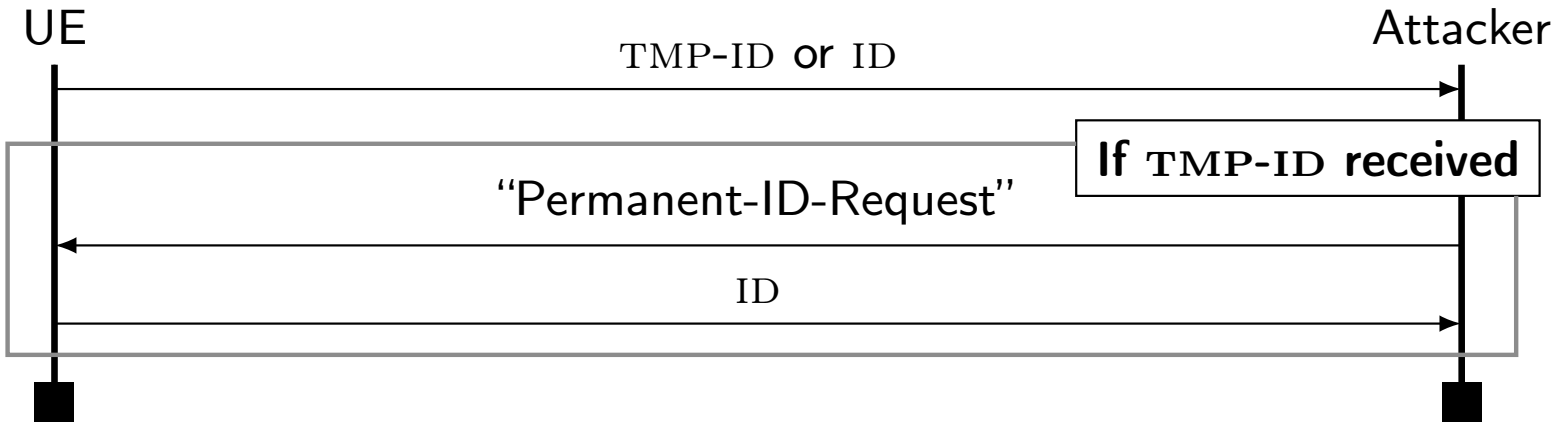

Why this is a major attack

- Reliable: the attack always works.
- Easy to deploy: only need an antenna.
- Large scale: not targeted.

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The 5G-AKA protocol

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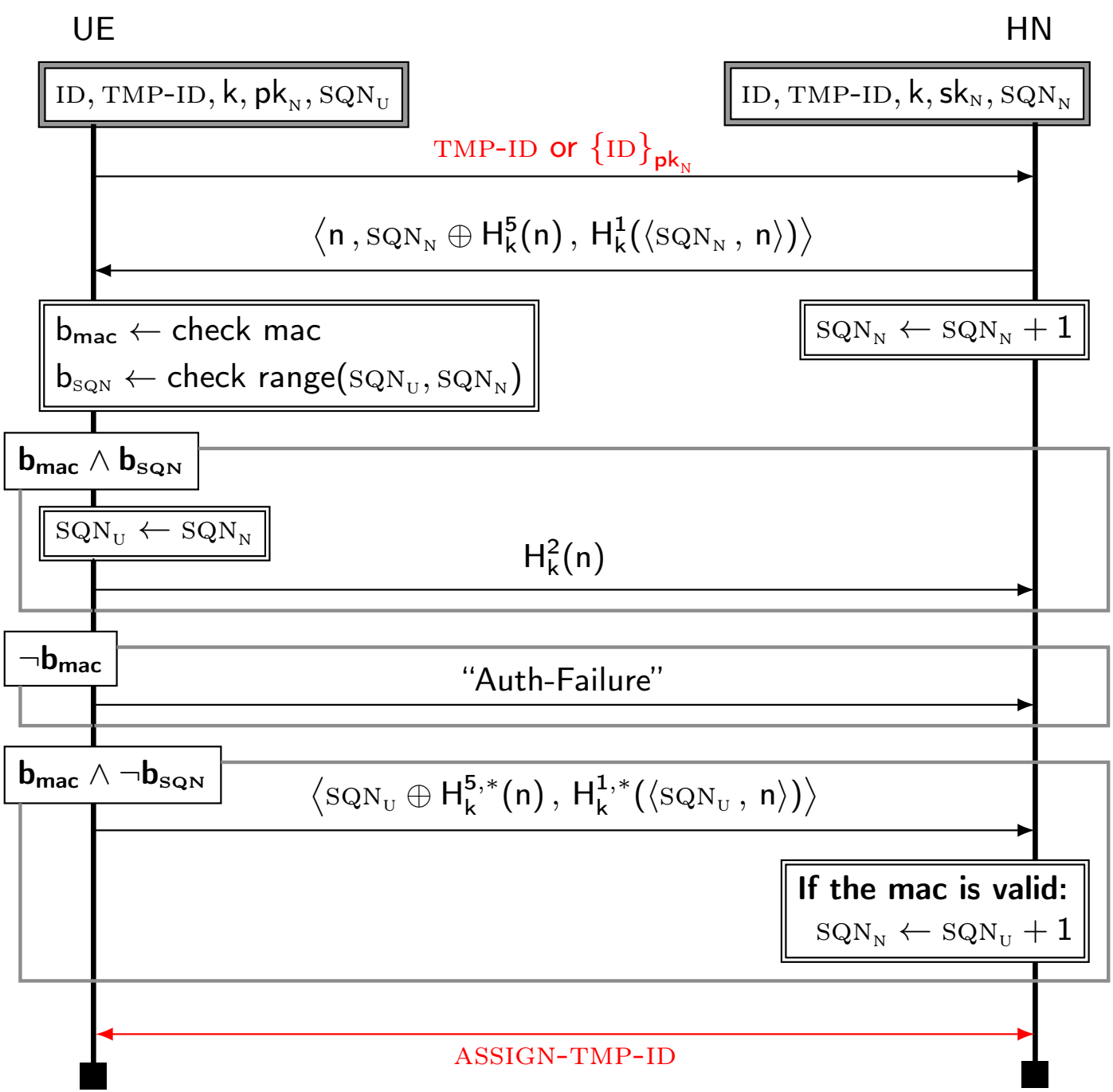
3GPP fix for 5G-AKA

Simply encrypt the permanent identity by sending $\{\mathrm{ID}\}_{\mathsf{pk}_\mathrm{N}}$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For confidentiality of the ID, yes.

For unlinkability, no.

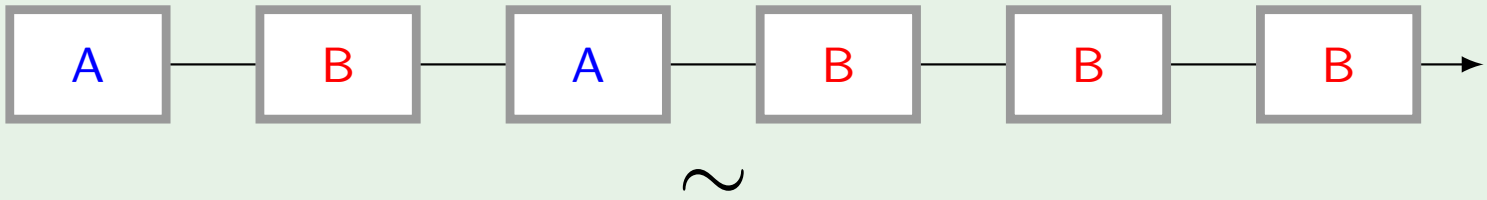
Unlinkability

Linkability Attack

Even if the ID is hidden, an attacker may link sessions of the same user.

Unlinkability

Example



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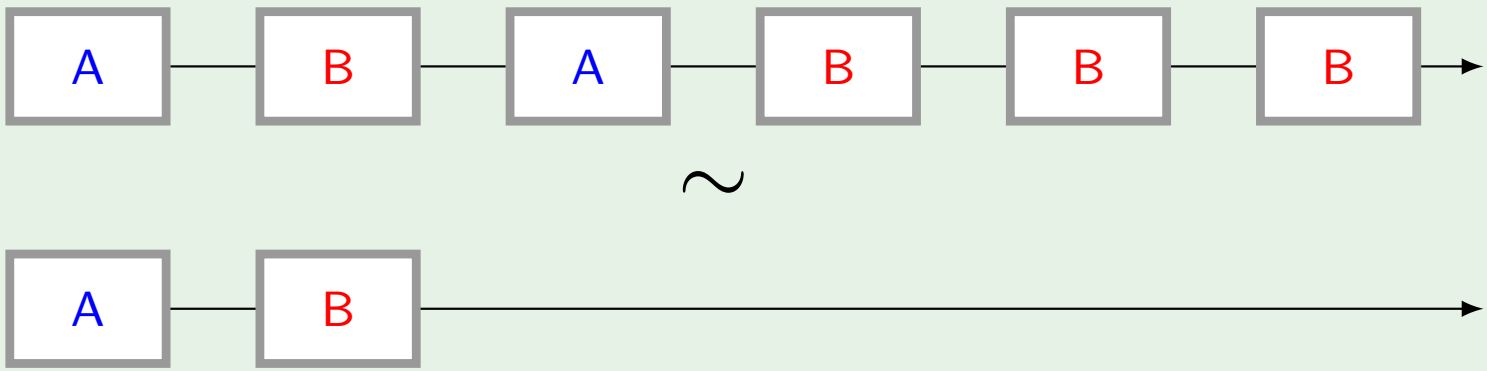

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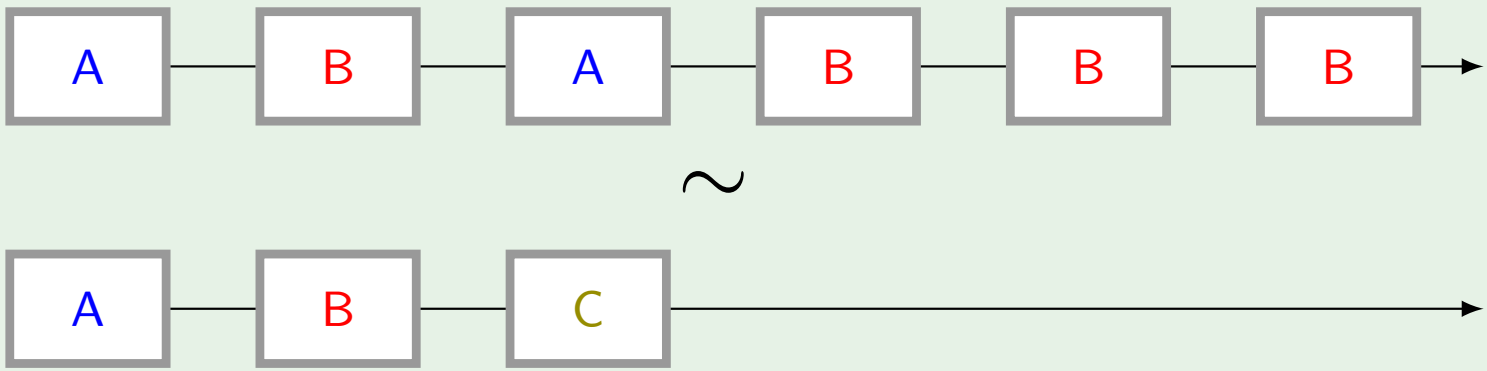

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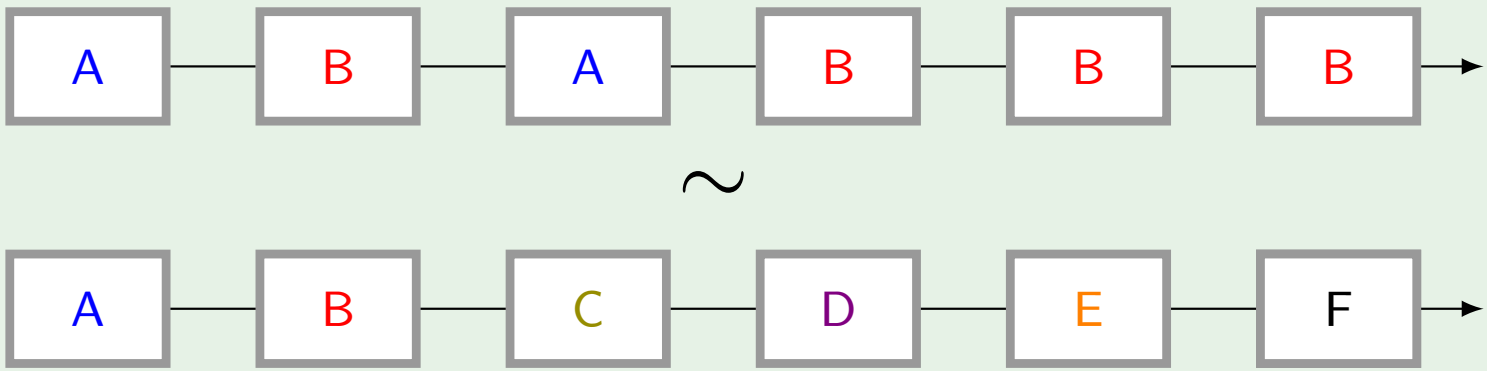

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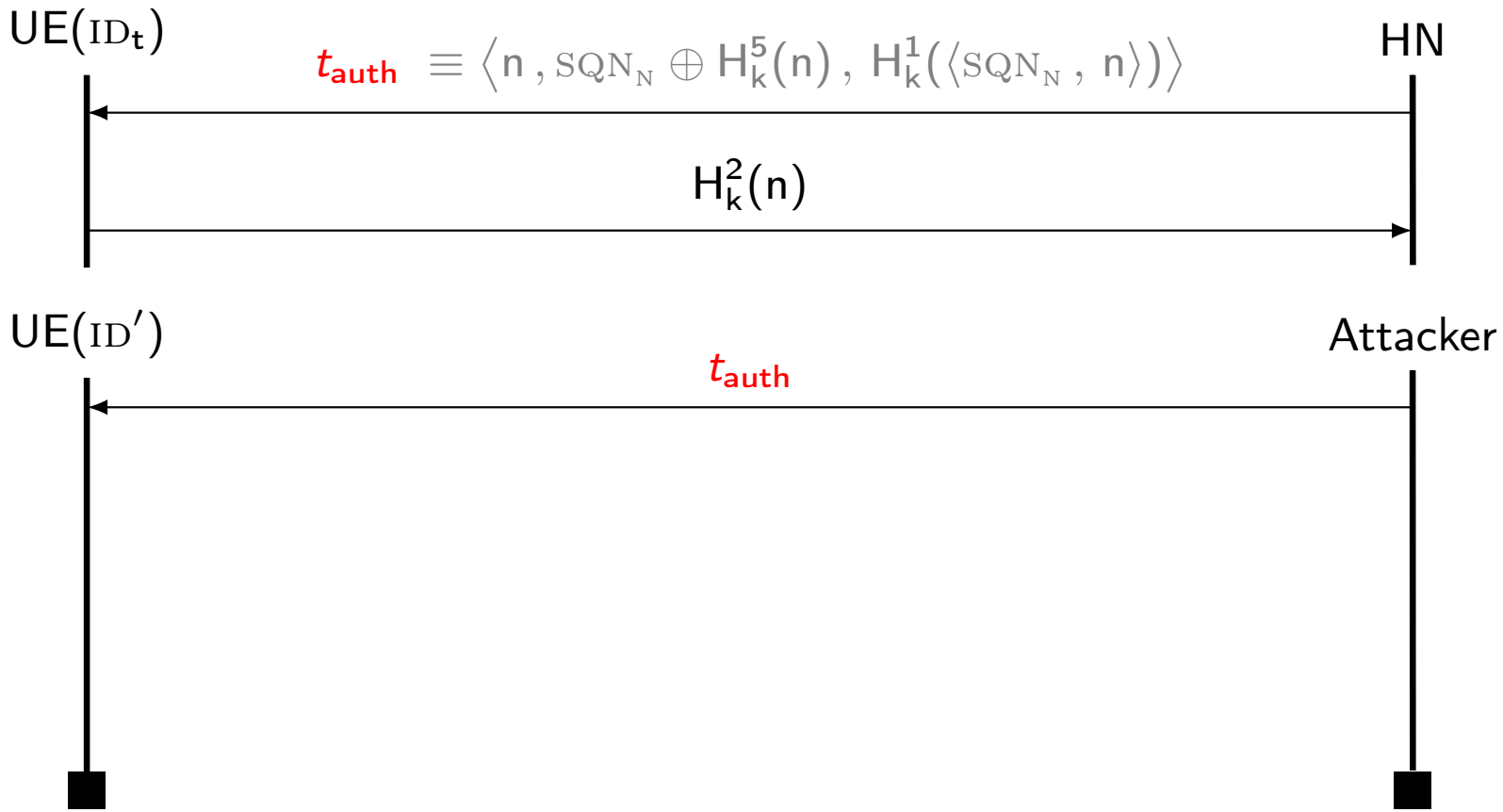

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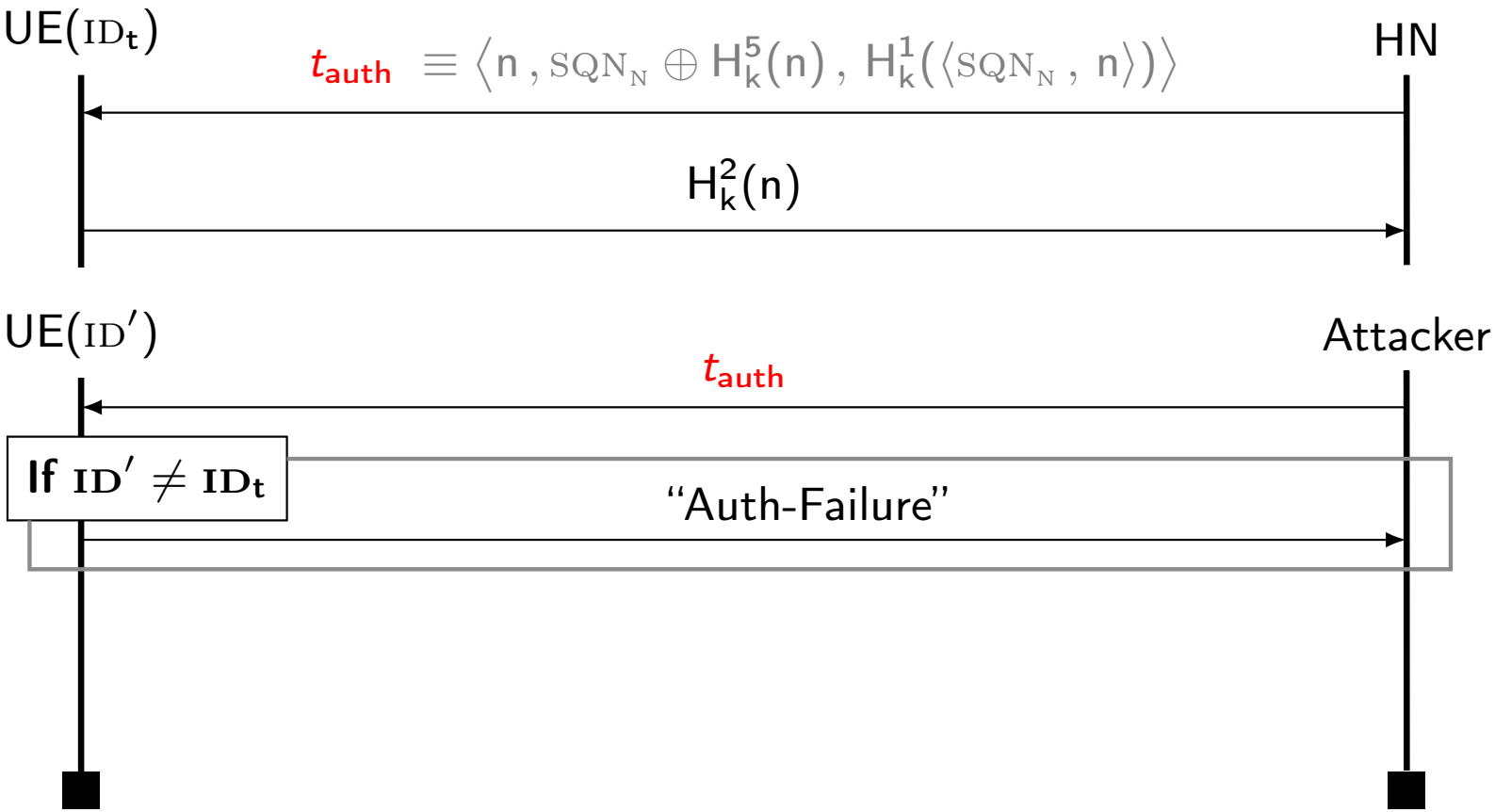

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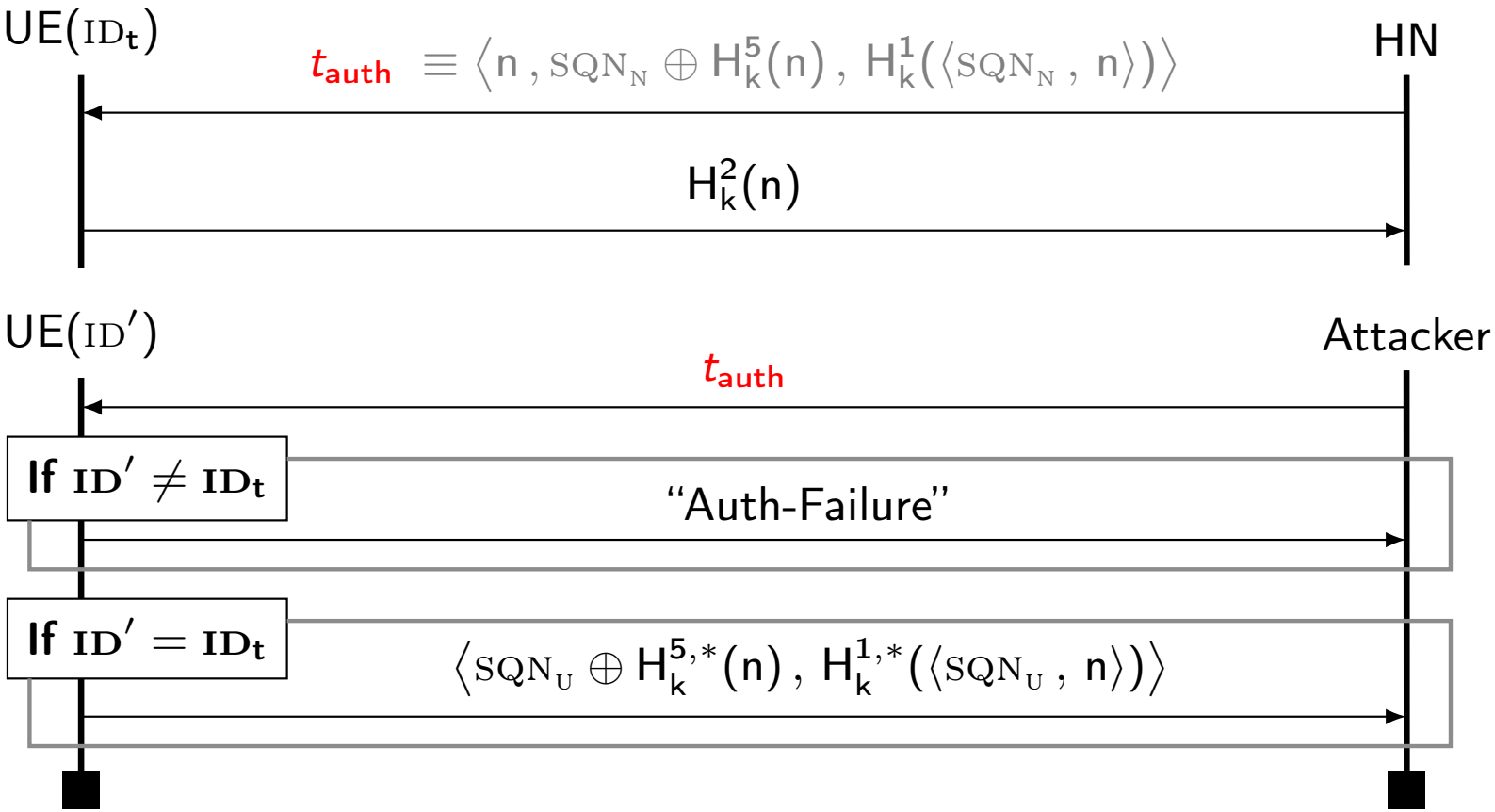

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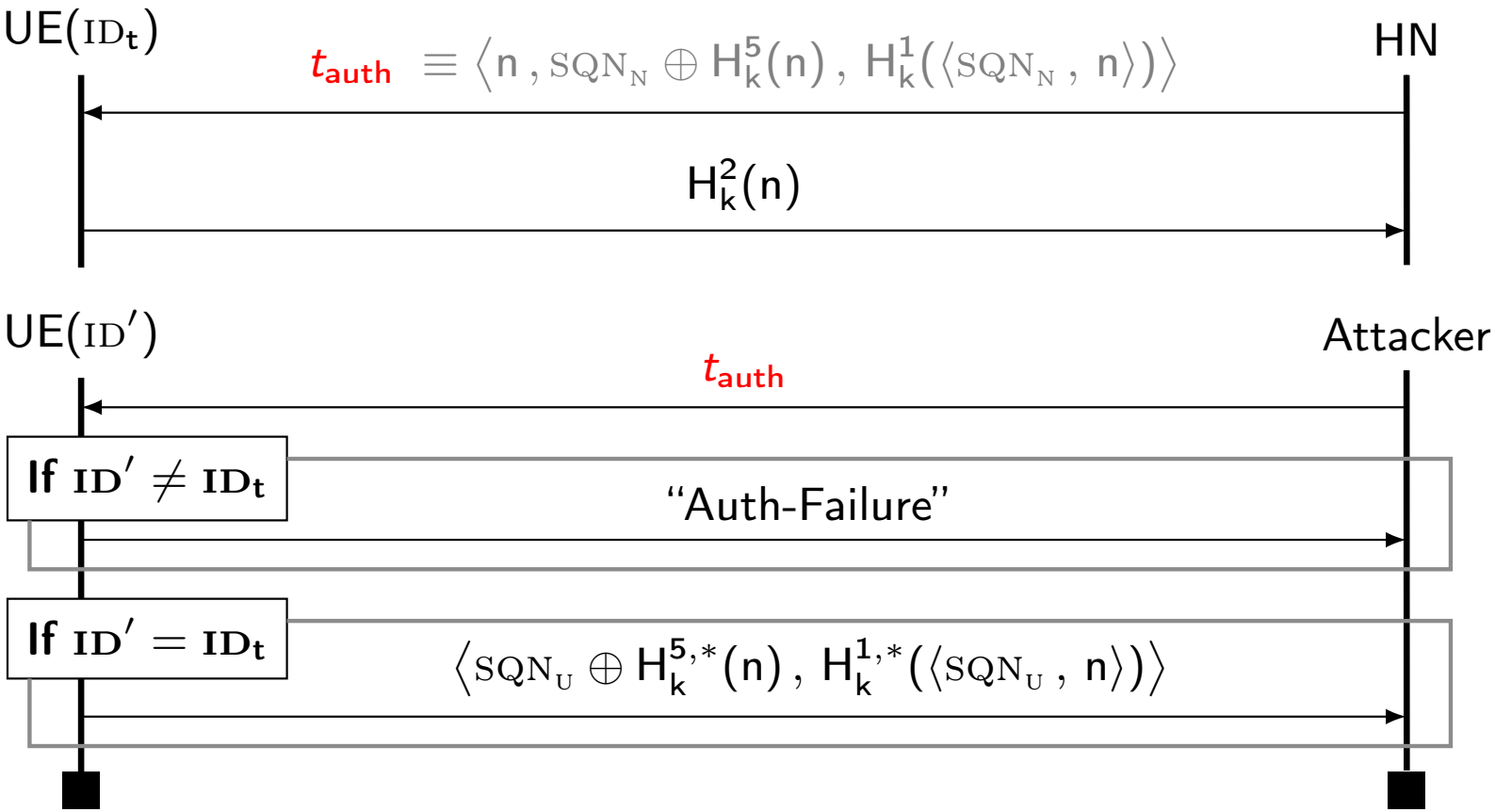

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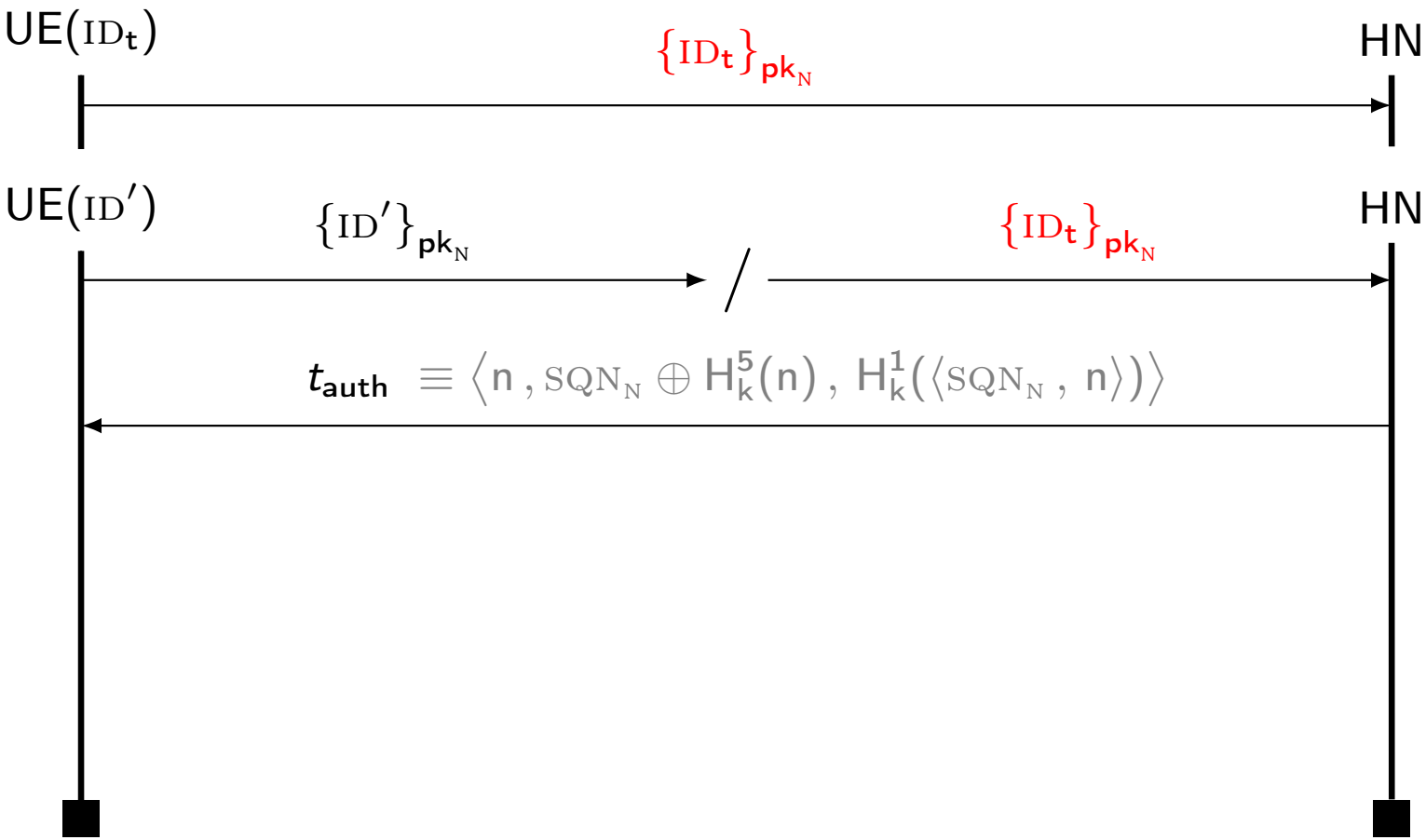

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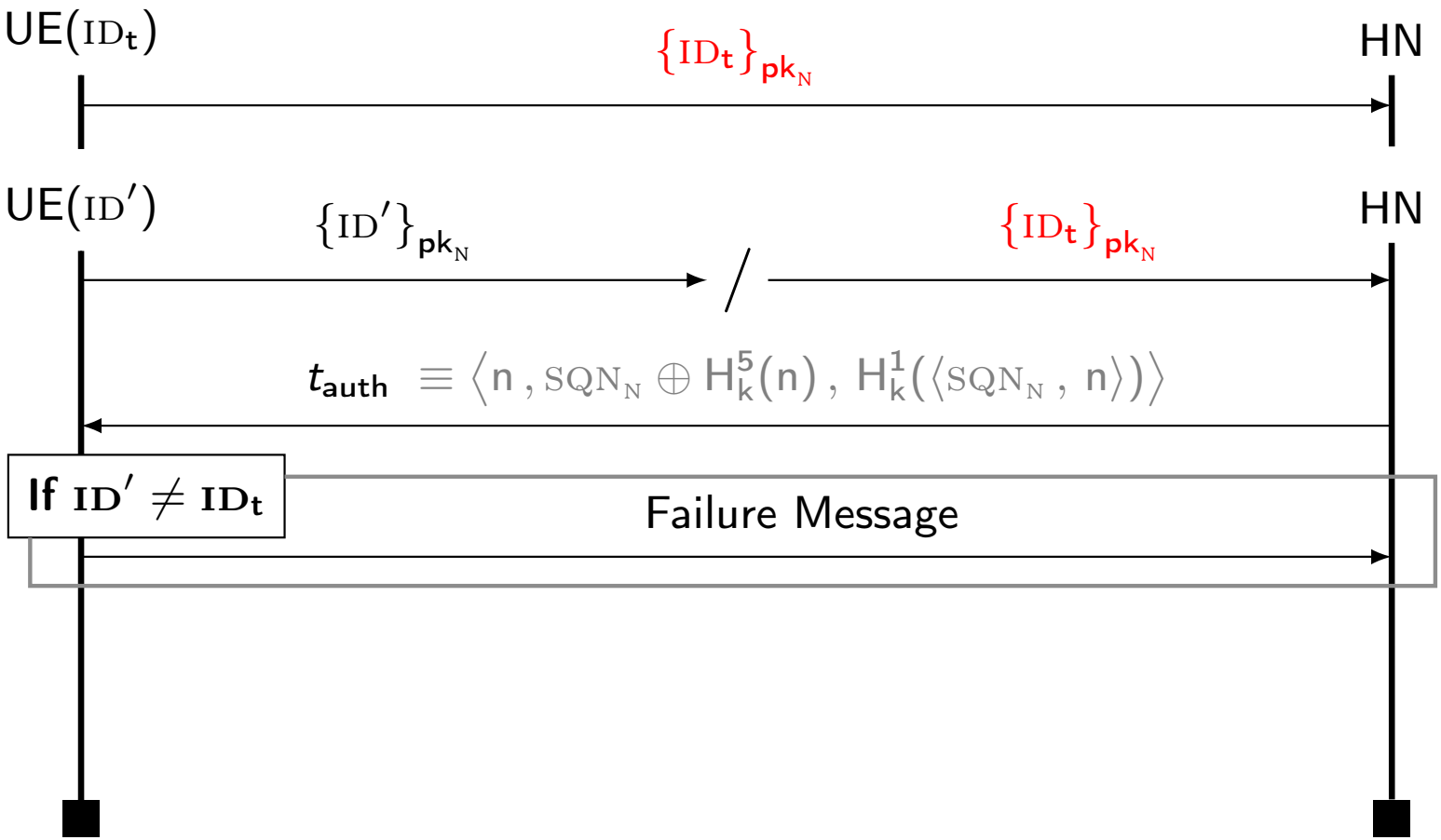

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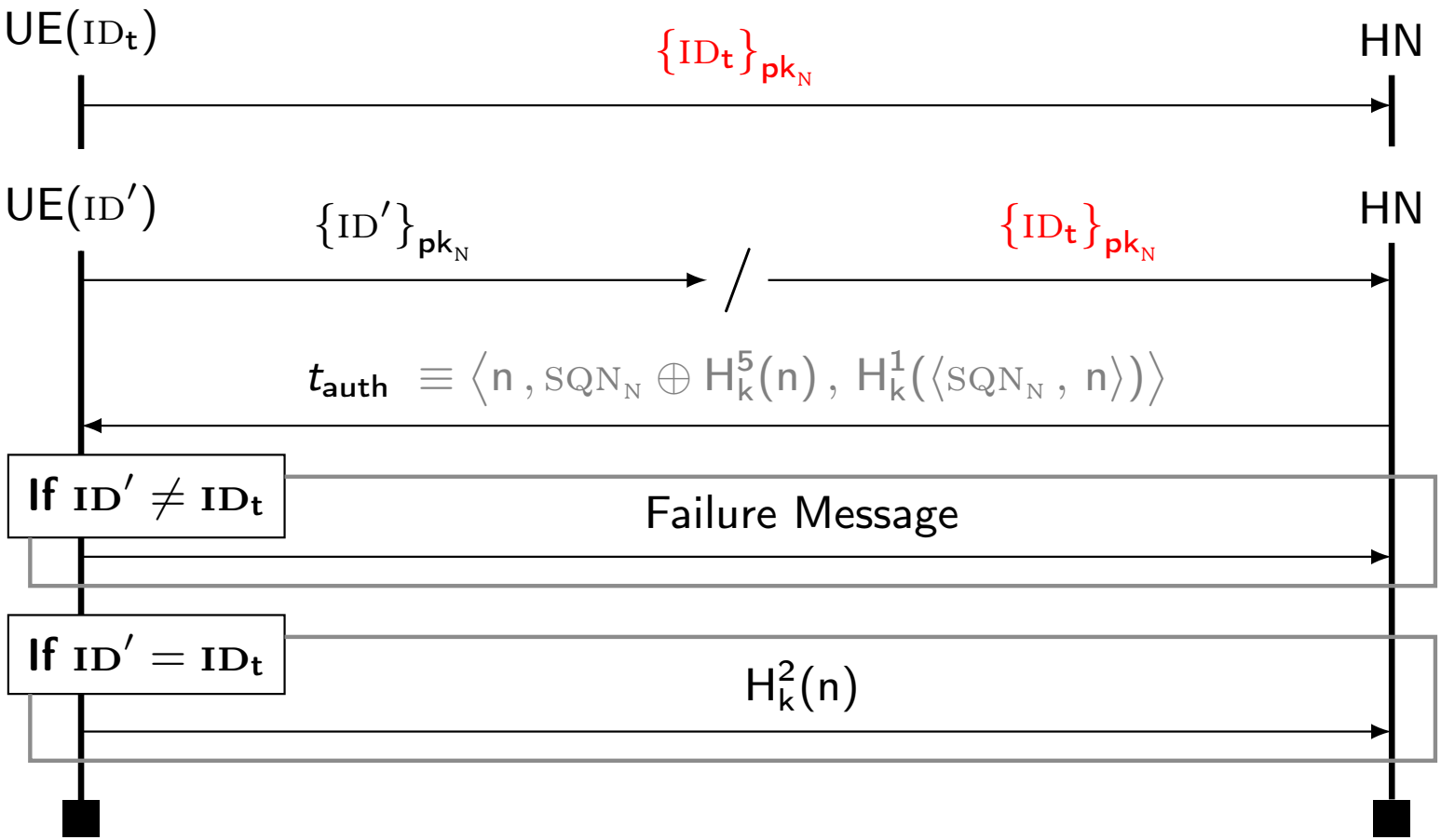

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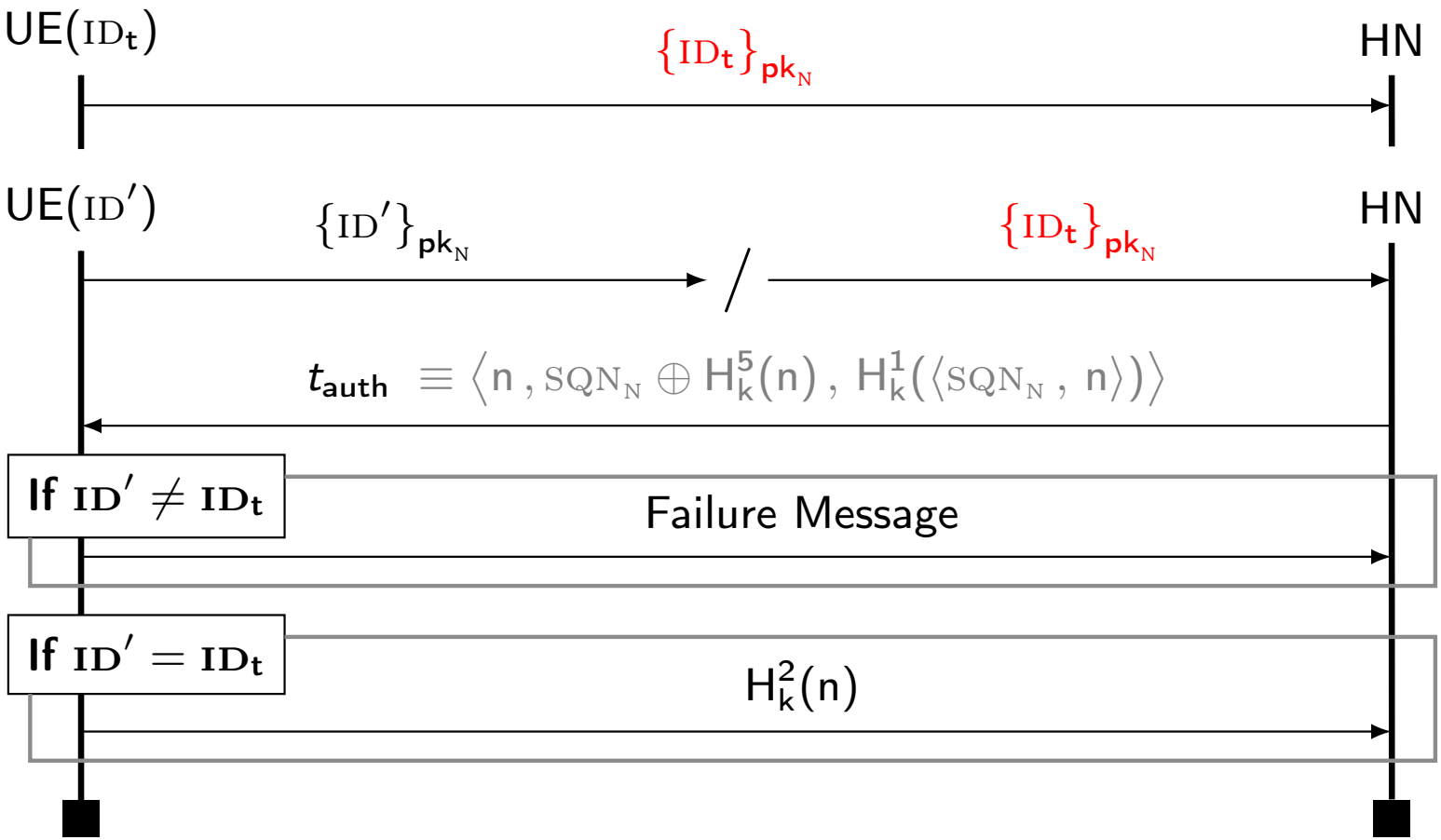

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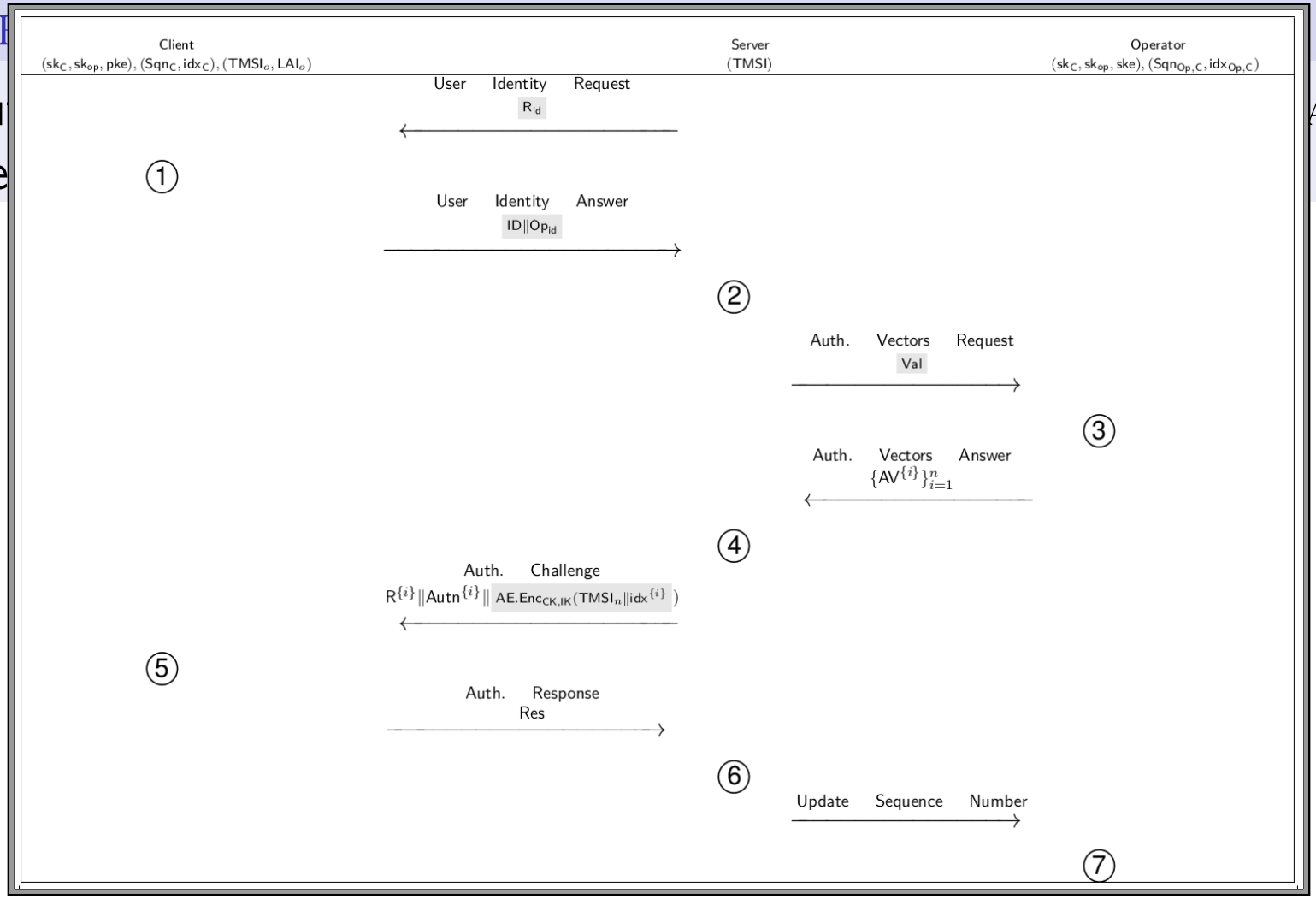

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- Send both t_1 and t_2, which increments $\mathrm{SQN_N}$ by **two**.
- The user is permanently de-synchronized $\Longrightarrow$ unlinkability attack.

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Design a modified version of AKA, called AKA$^+$, such that:

- Provides some form of unlinkability.
- Satisfies the design and efficiency constraints of 5G-AKA.
- Is proved secure.

Random Number Generation in 5G-AKA

Random Number Generation by the User

In 5G-AKA, the user generates a random number only:

- If no TMP-ID is assigned.
- In the session following a de-synchronization.

The AKA$^+$ Protocol

Design Constraints

AKA$^+$ should be as efficient as the 5G-AKA:

- Random number generation (user): at most one nonce per session, and only for re-synchronization or if no TMP-ID is assigned.

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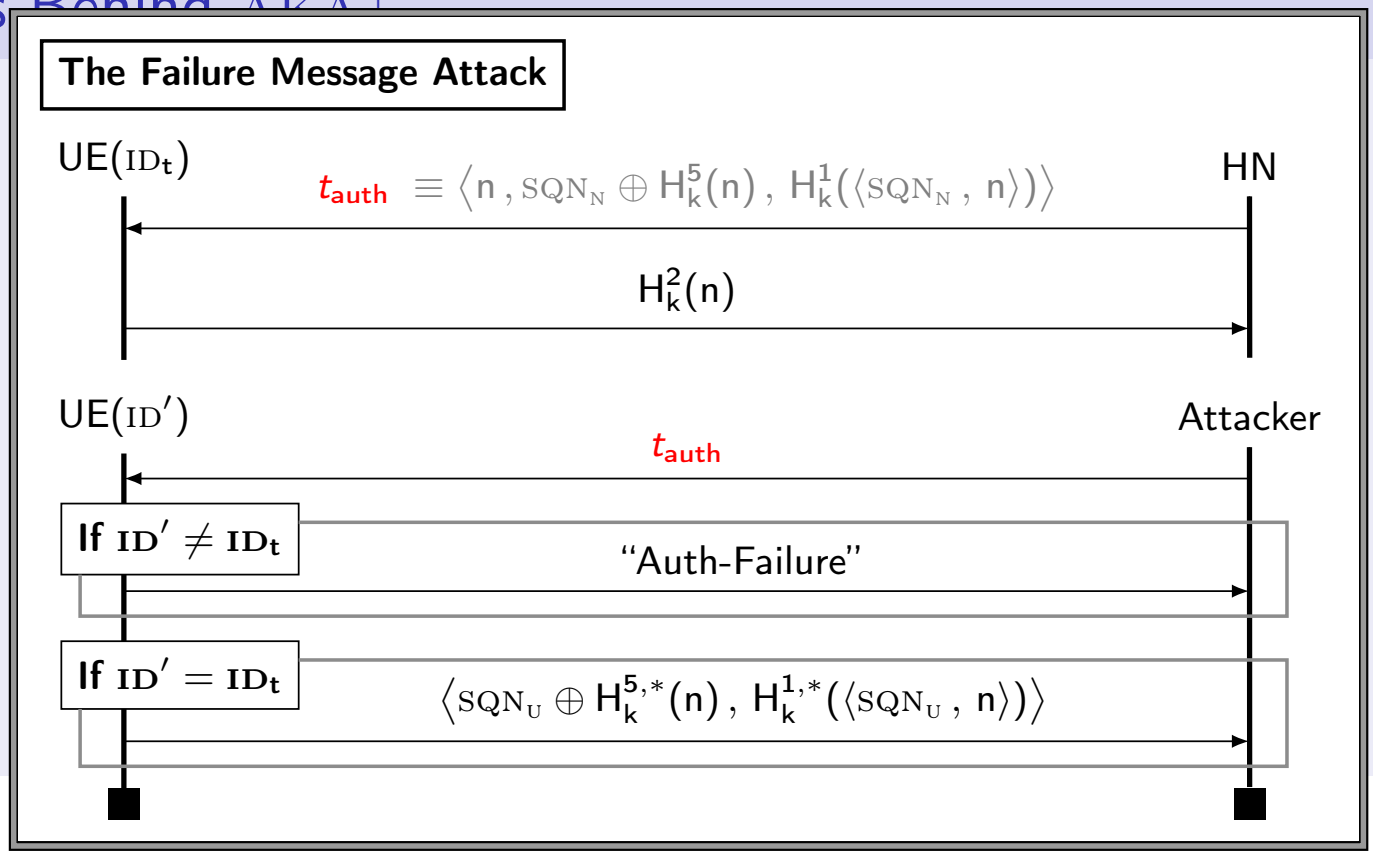
- Network complexity: only three messages per session.

Key Ideas

Key Ideas Behind AKA$^+$

Key Ideas

Key Ideas Behind AKA+



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  - N
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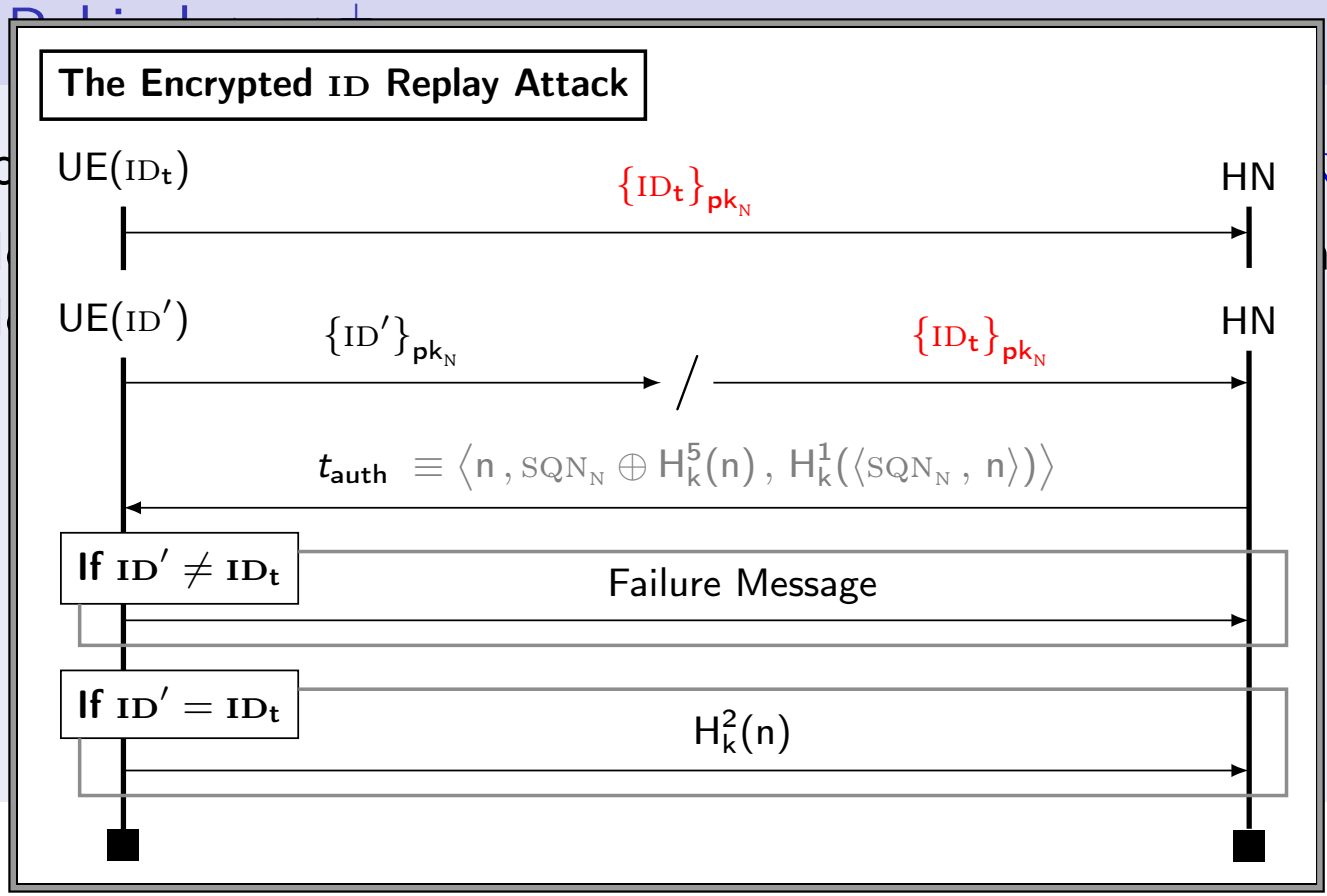

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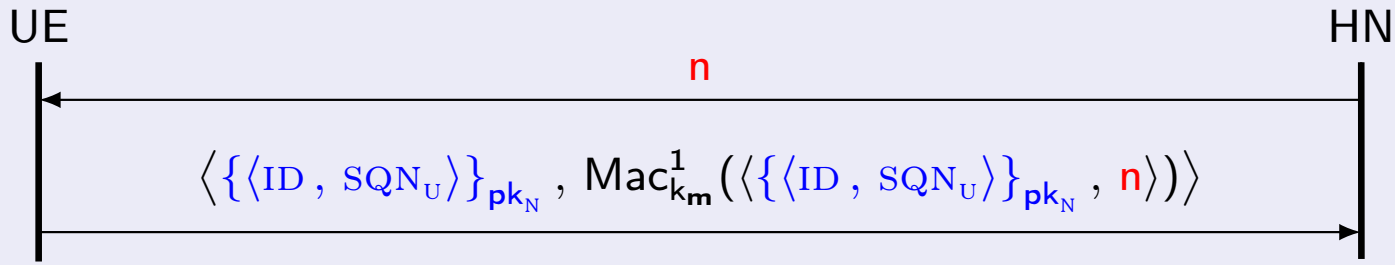

Architecture of AKA$^+$

AKA$^+$ Sub-Protocols

- ID sub-protocol:
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ID Sub-Protocol

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- ASSIGN-TMP-ID sub-protocol:
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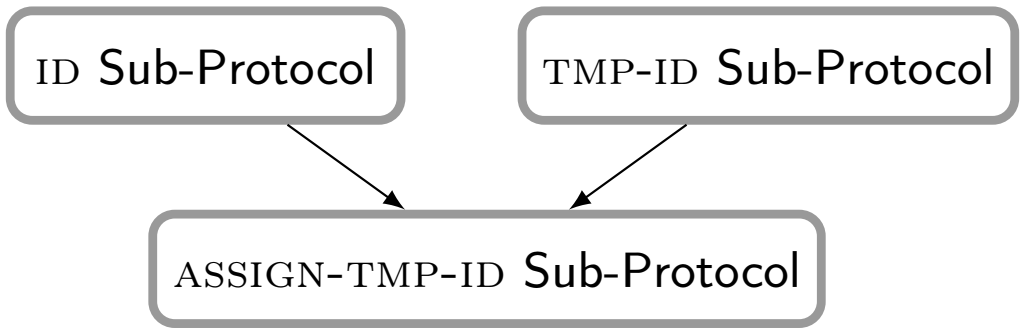
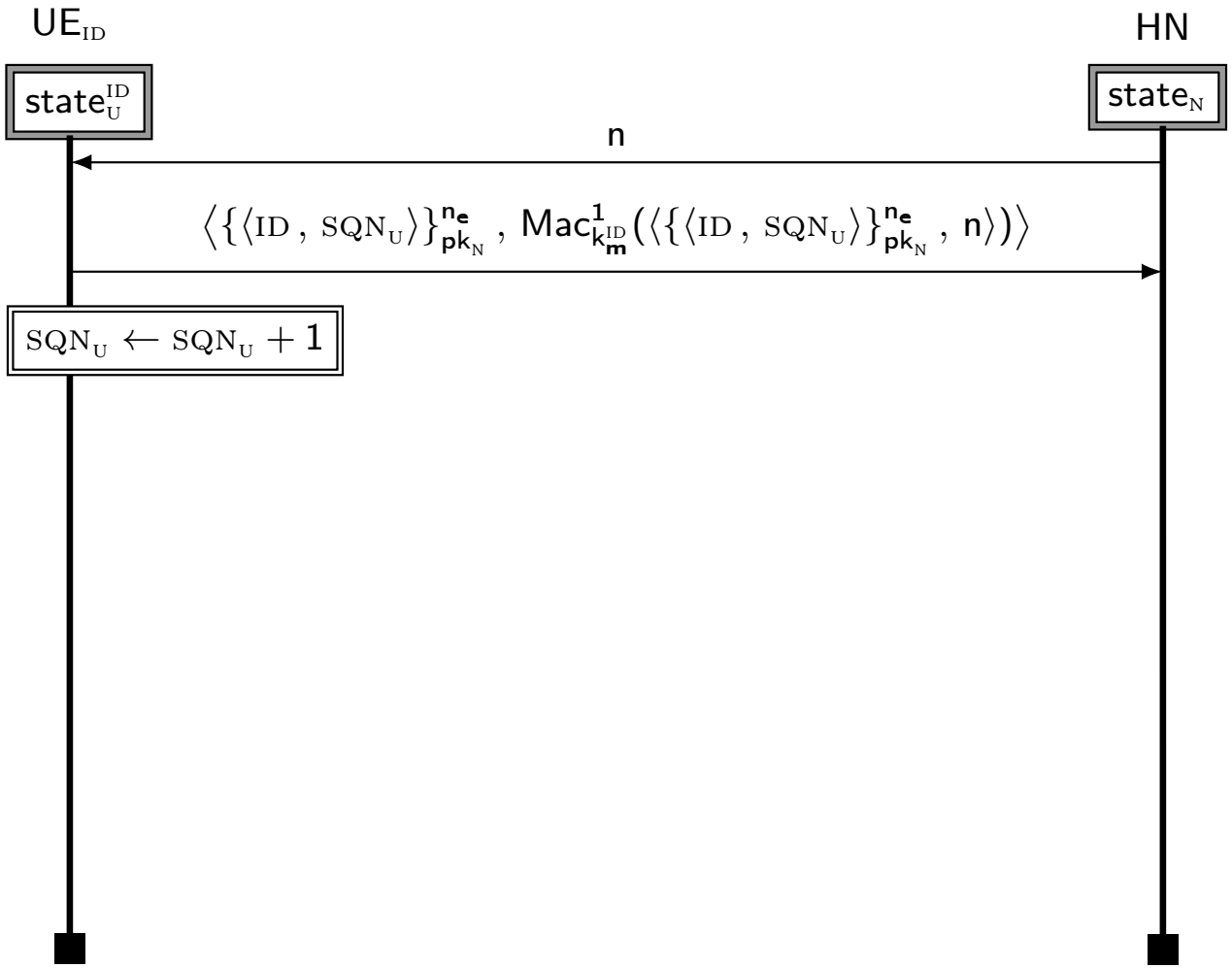


ID
Sub-Protocol



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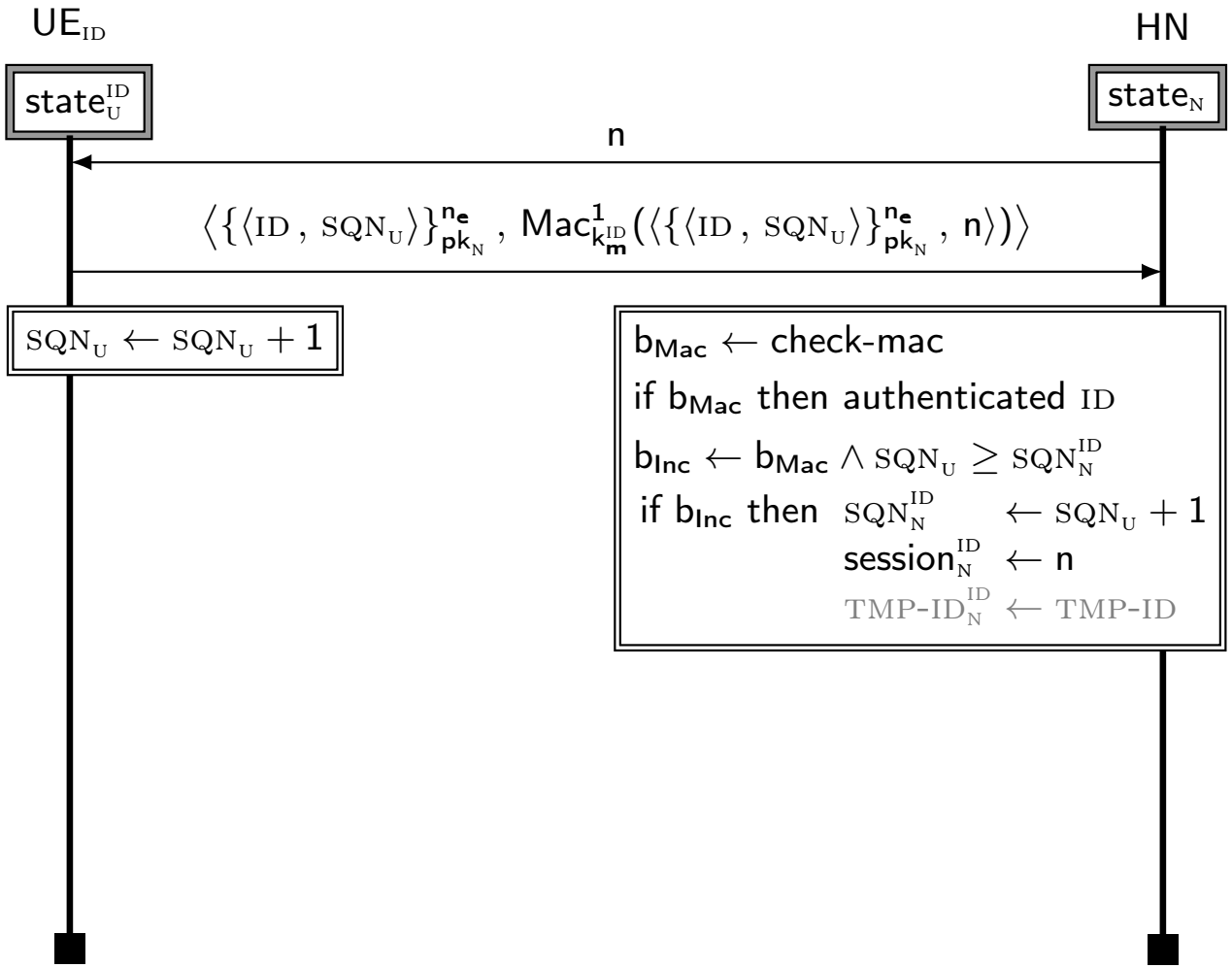

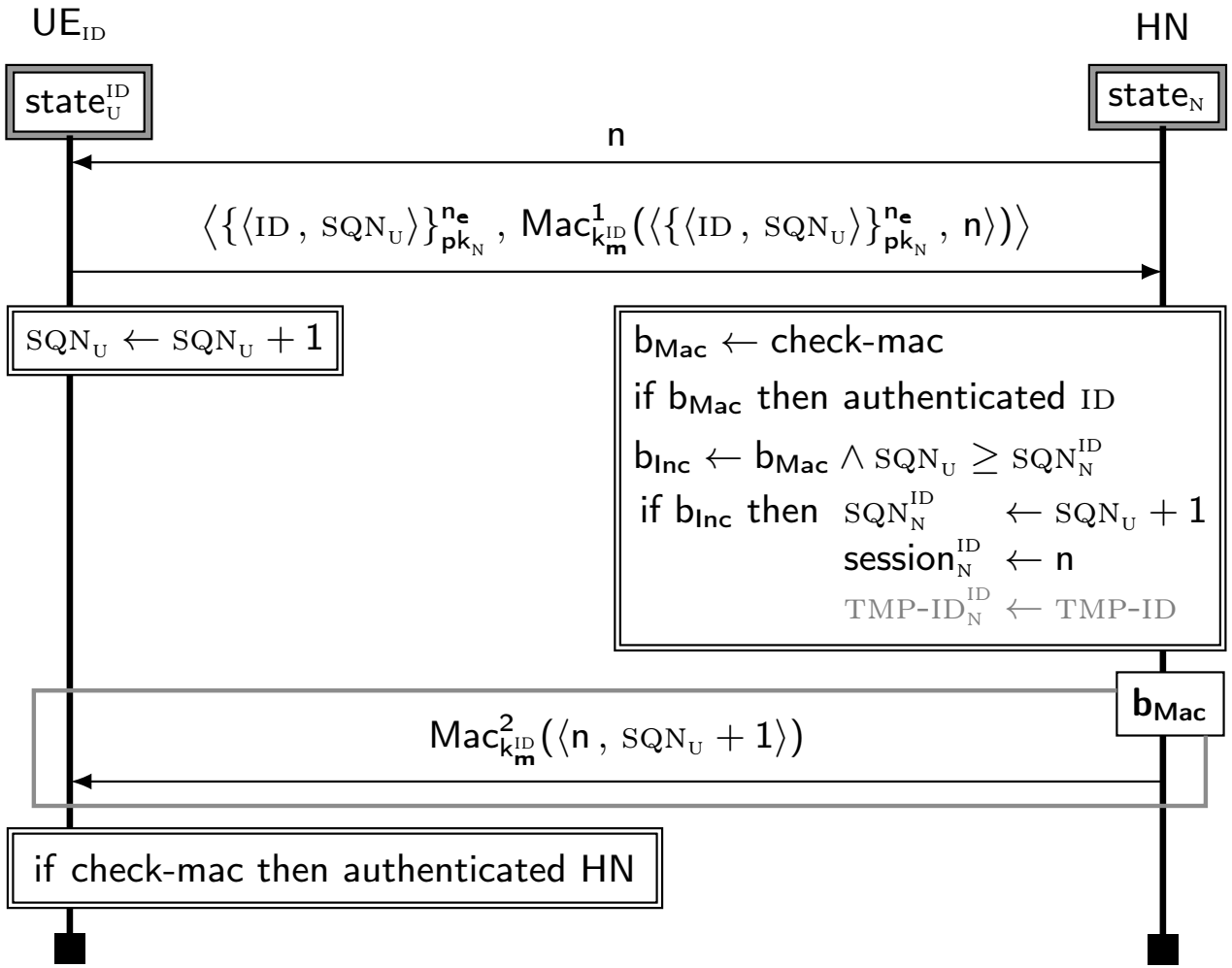
UE_ID
HN
state_U^ID
state_N
n
⟨{⟨ID , SQN_U⟩}^{n_e}_{pk_N} , Mac^1_{k^ID_m}(⟨{⟨ID , SQN_U⟩}^{n_e}_{pk_N} , n⟩)⟩
SQN_U ← SQN_U + 1
b_Mac ← check-mac
if b_Mac then authenticated ID
b_Inc ← b_Mac ∧ SQN_U ≥ SQN_N^ID
if b_Inc then SQN_N^ID ← SQN_U + 1
session_N^ID ← n
TMP-ID_N^ID ← TMP-ID
b_Mac
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TMP-ID
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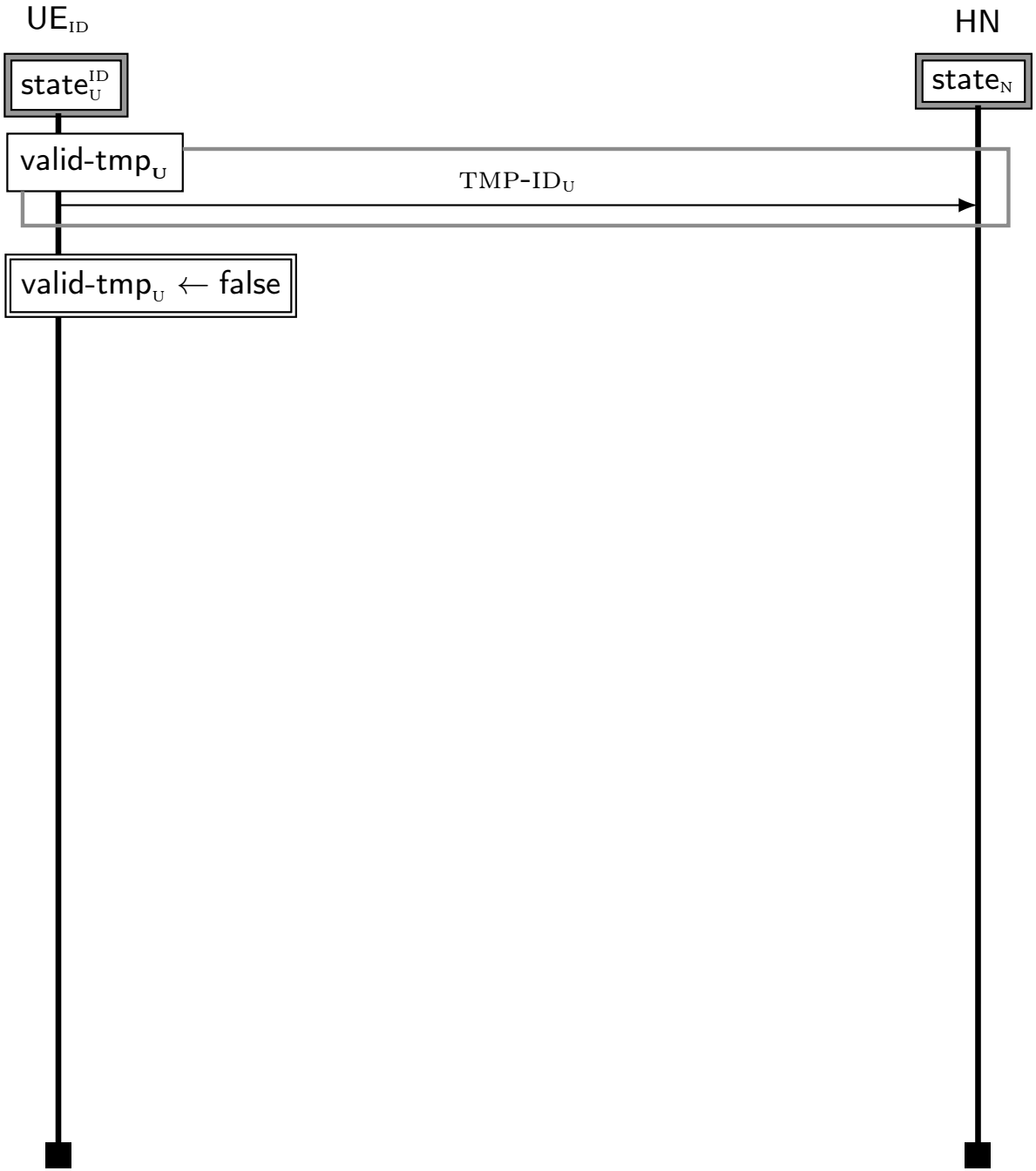

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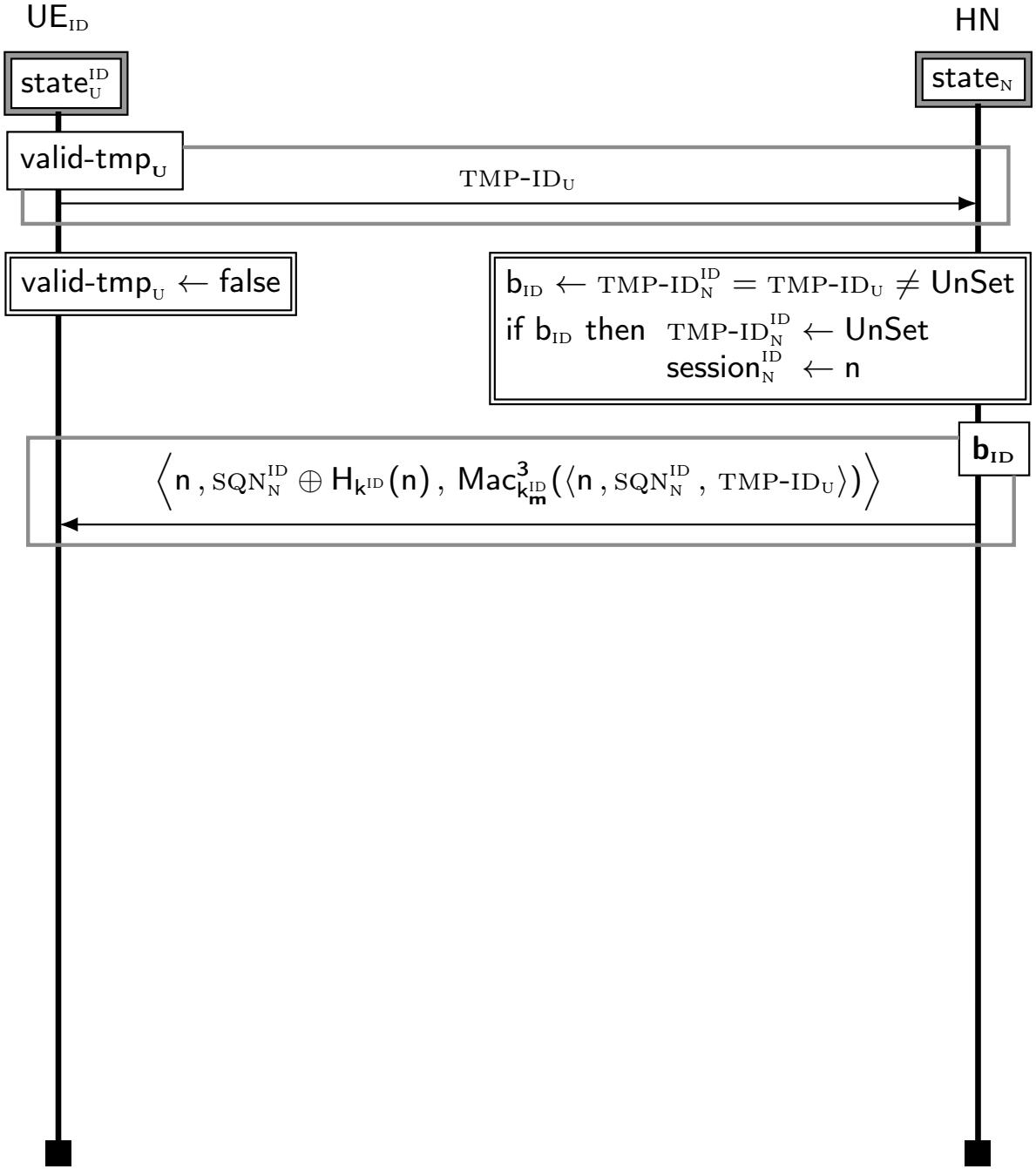

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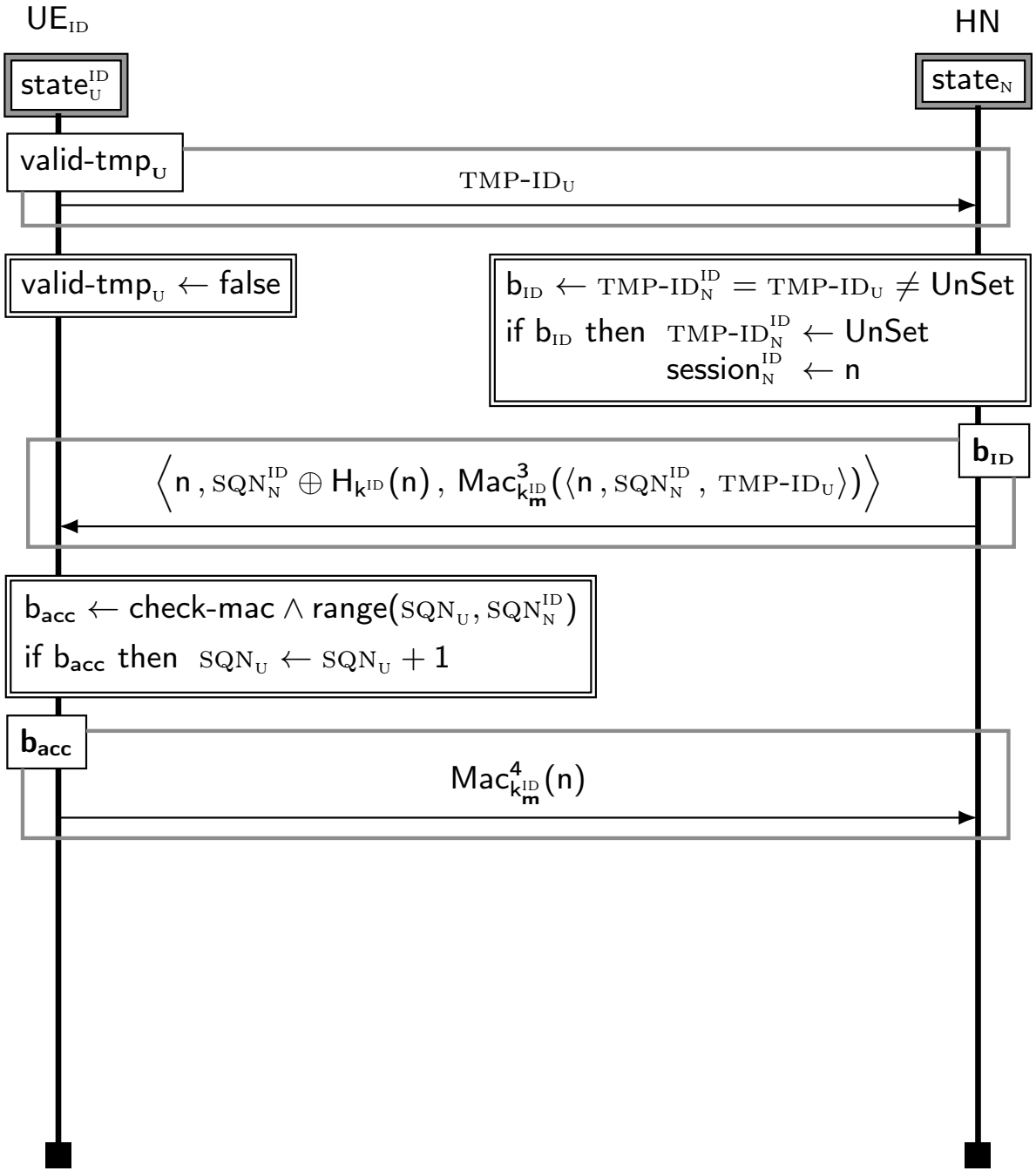

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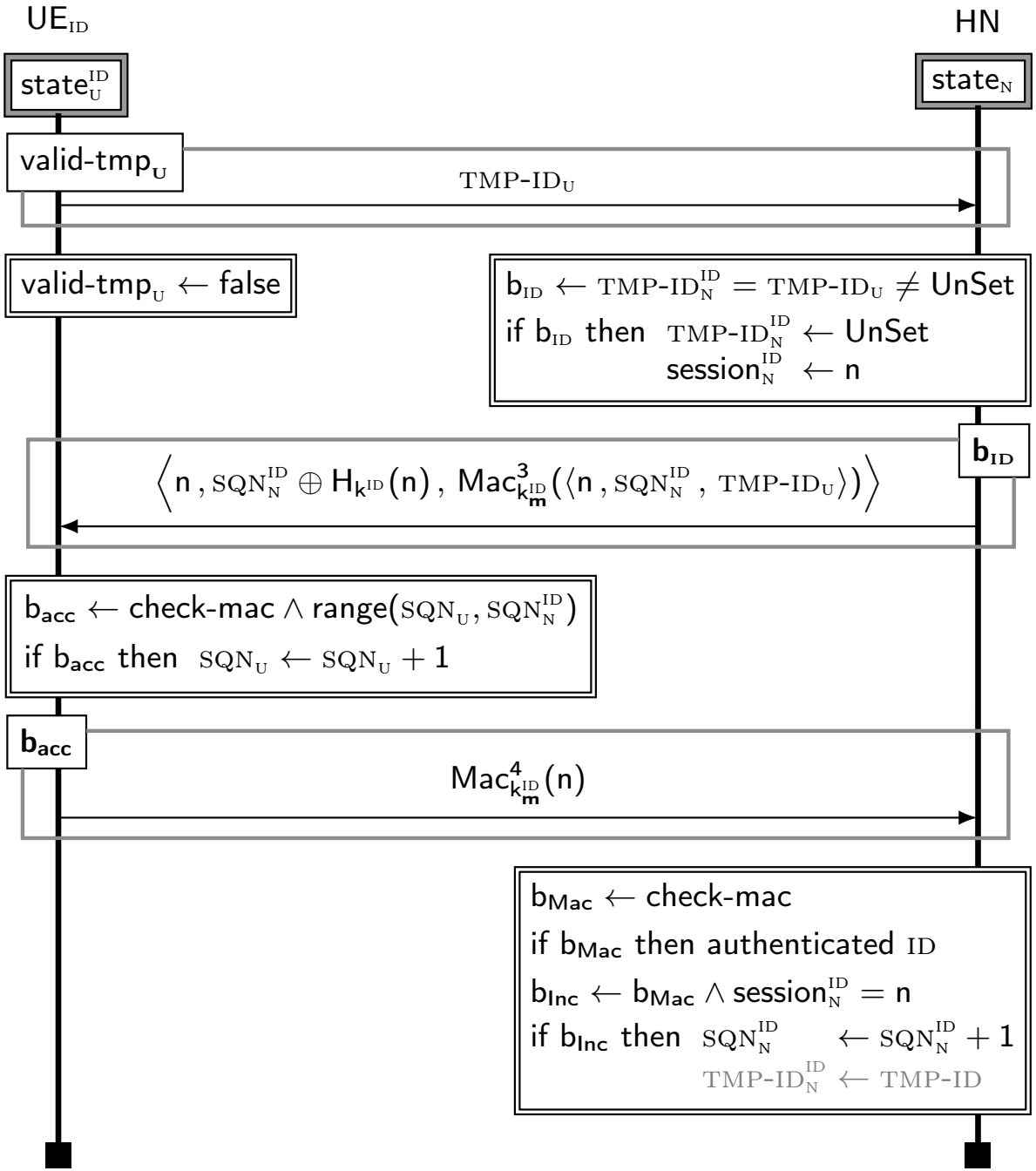

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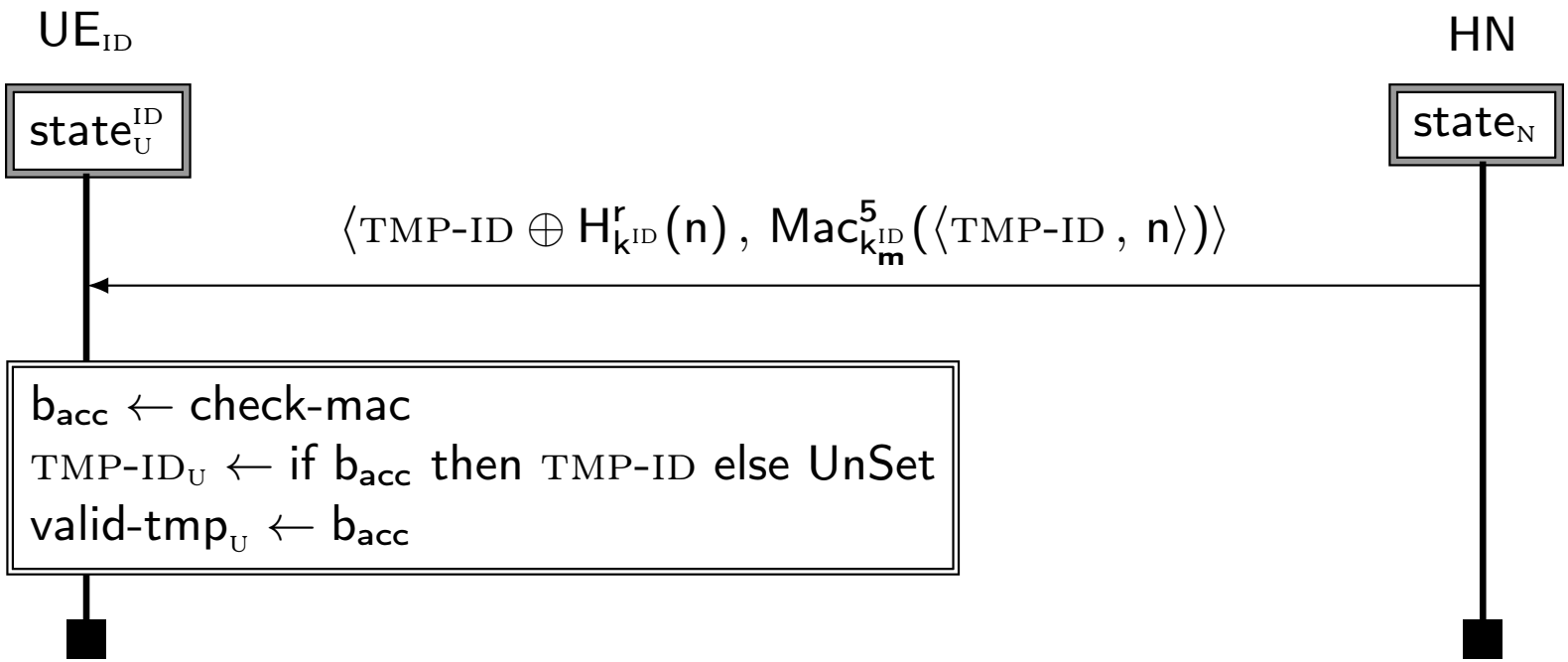

Security Proofs

Objective

Formally prove that AKA^+ satisfies:

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Objecti

Formally

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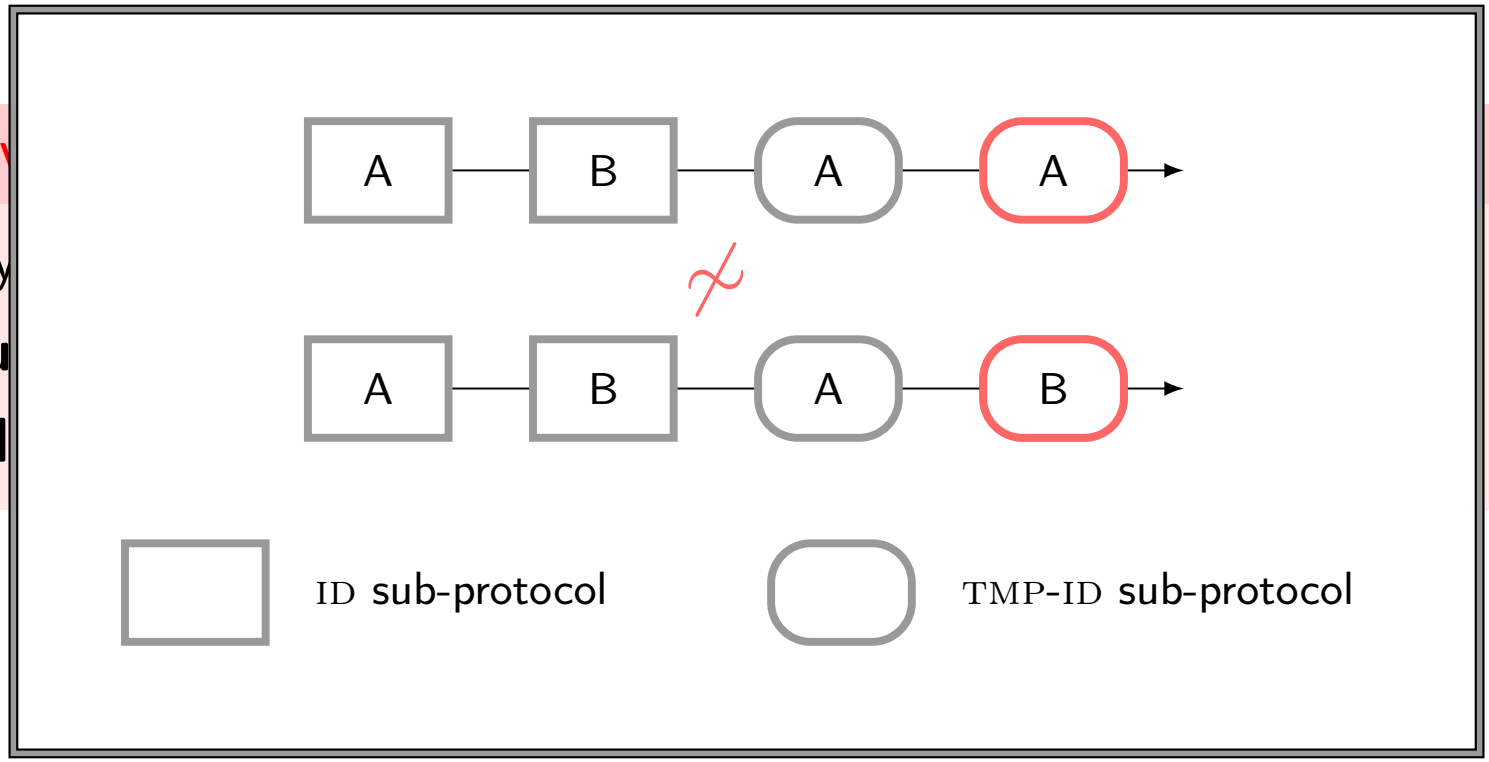
- **unl**



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High level idea: show privacy only for a subset of the standard unlinkability game scenarios.

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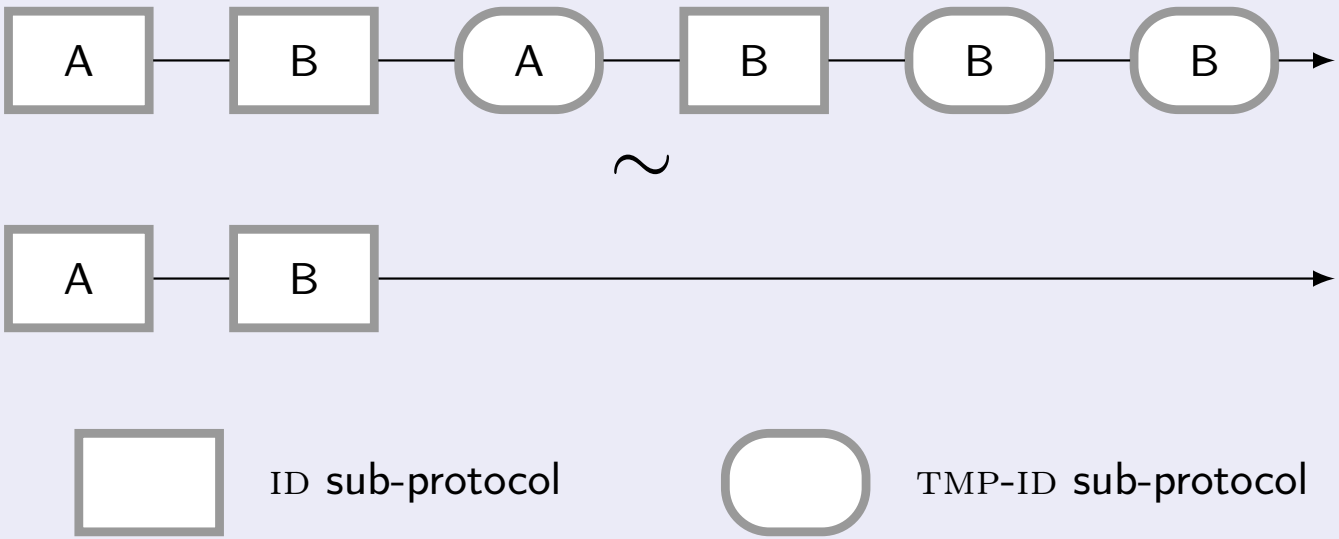
- Game-based definition (like standard unlinkability).
- Parametric property (σ).
- In general, weaker than unlinkability.
- Allow to precisely quantify privacy guarantees.

The σ-Unlinkability Property

Two Indistinguishable Executions

Each time the ID sub-protocol is used, we can change the user's identity.



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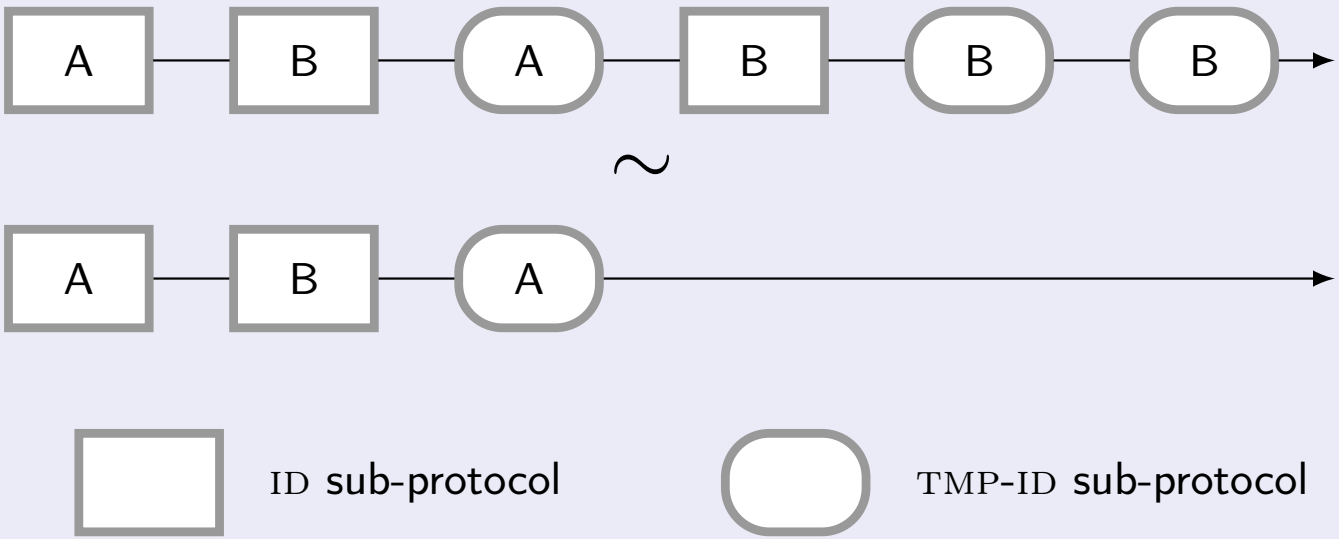

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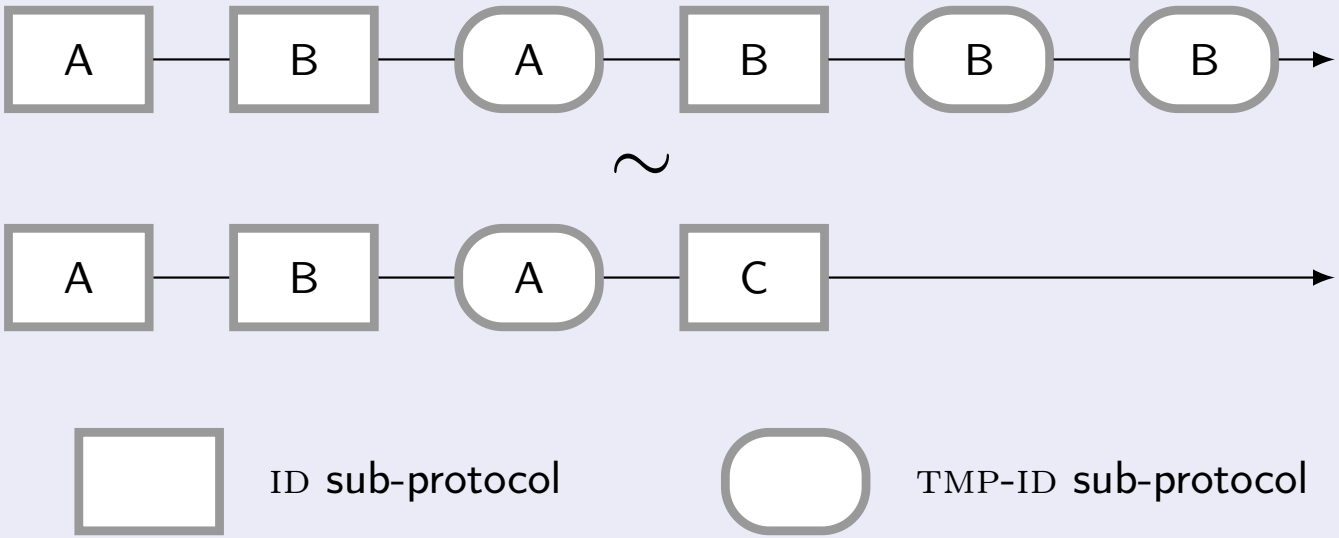

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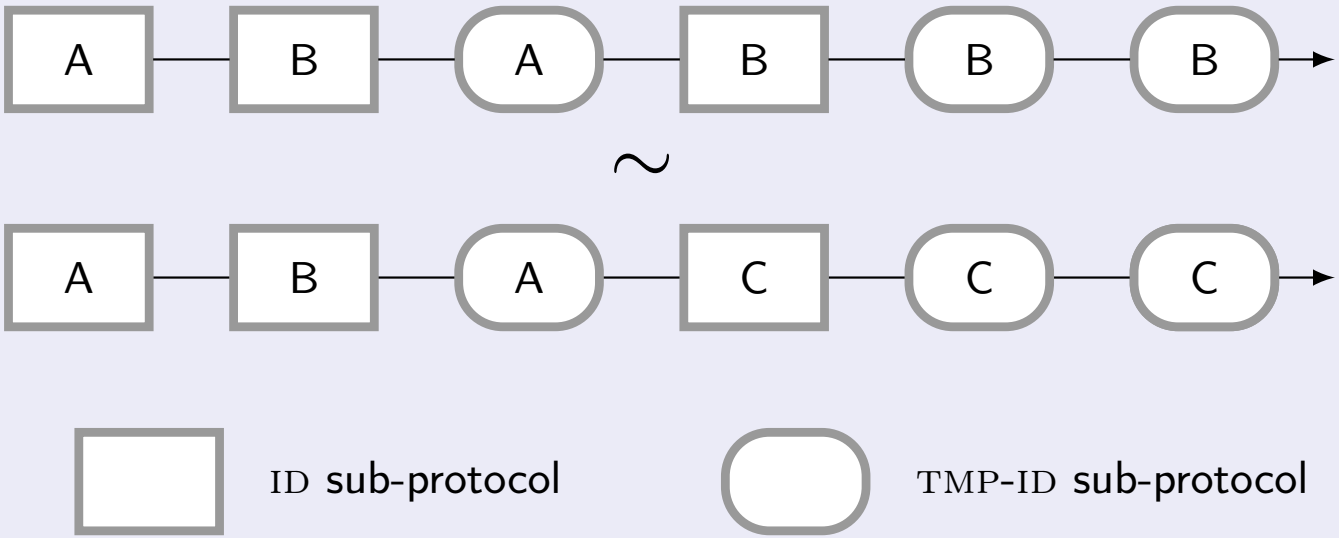

σ-Unlinkability

Efficiency vs Privacy

There is a trade-off between:

- **Efficiency:** the TMP-ID sub-protocol is faster.
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Remark

- If we use only the ID sub-protocol, we get standard unlinkability.
- All previous attacks are also σ-unlinkability attacks.

Modeling

The Bana-Comon Model [Bana and Comon-Lundh, 2014]

The proof is in the Bana-Comon unlinkability model:

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- We have to show that $\mathsf{Ax} \models \vec{u}_P \sim \vec{u}_Q$.

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  Example: $\tau = \mathsf{UE}_A, \mathsf{HN}, \mathsf{UE}_B, \mathsf{UE}_A$.

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- **Symbolic trace** of actions τ.
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- **Symbolic frame** ϕ_τ: sequences of messages observed by the attacker.
- **Symbolic state** σ_τ: current state of the users and the network.

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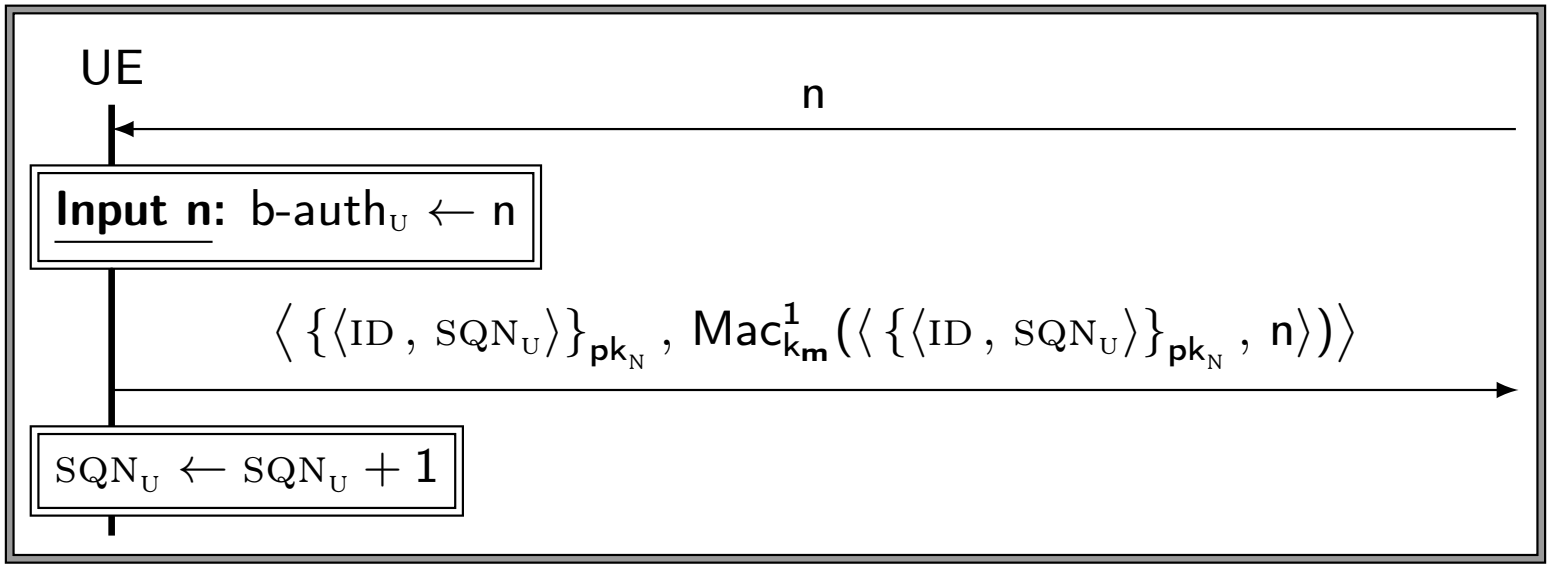

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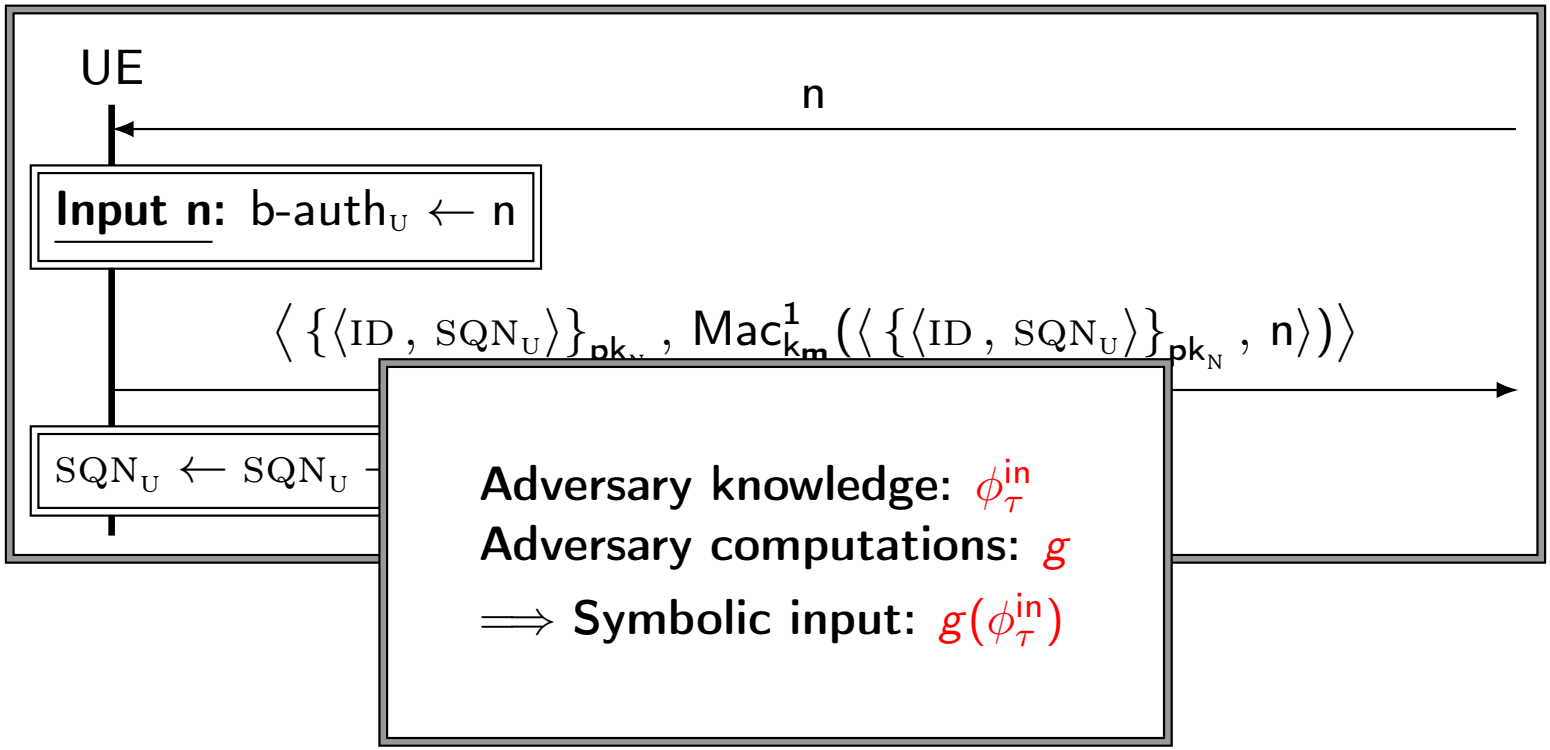

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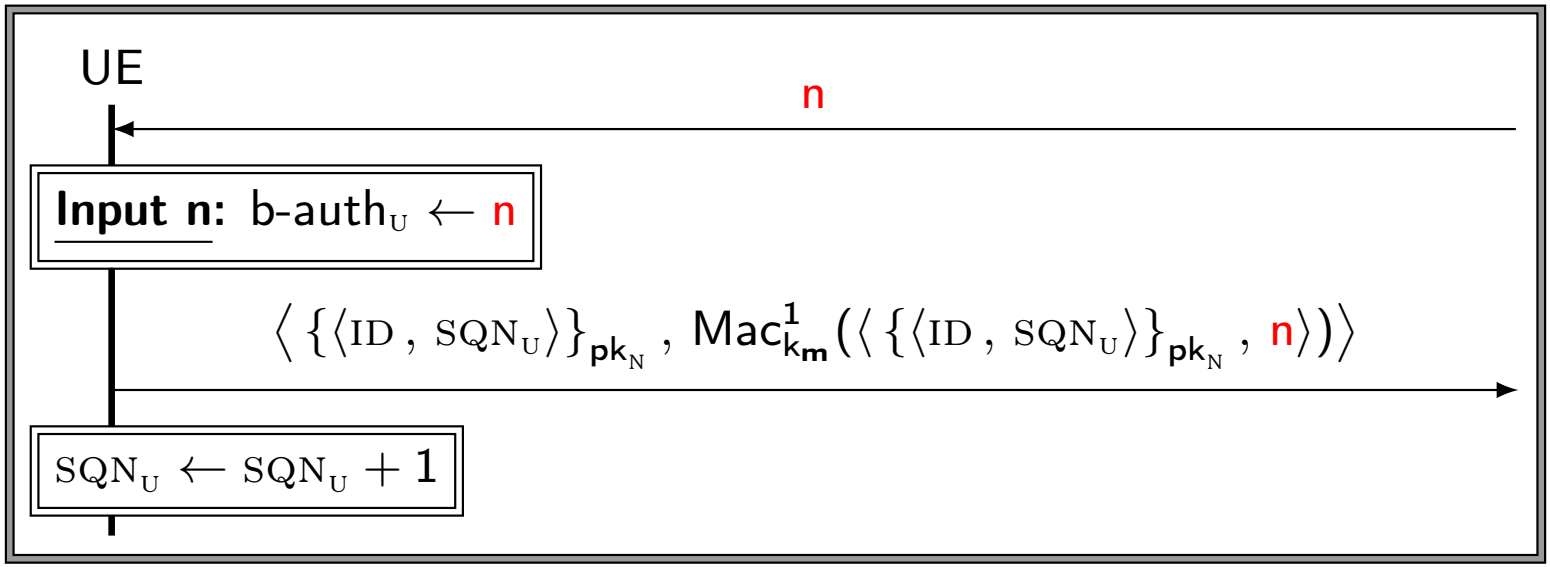

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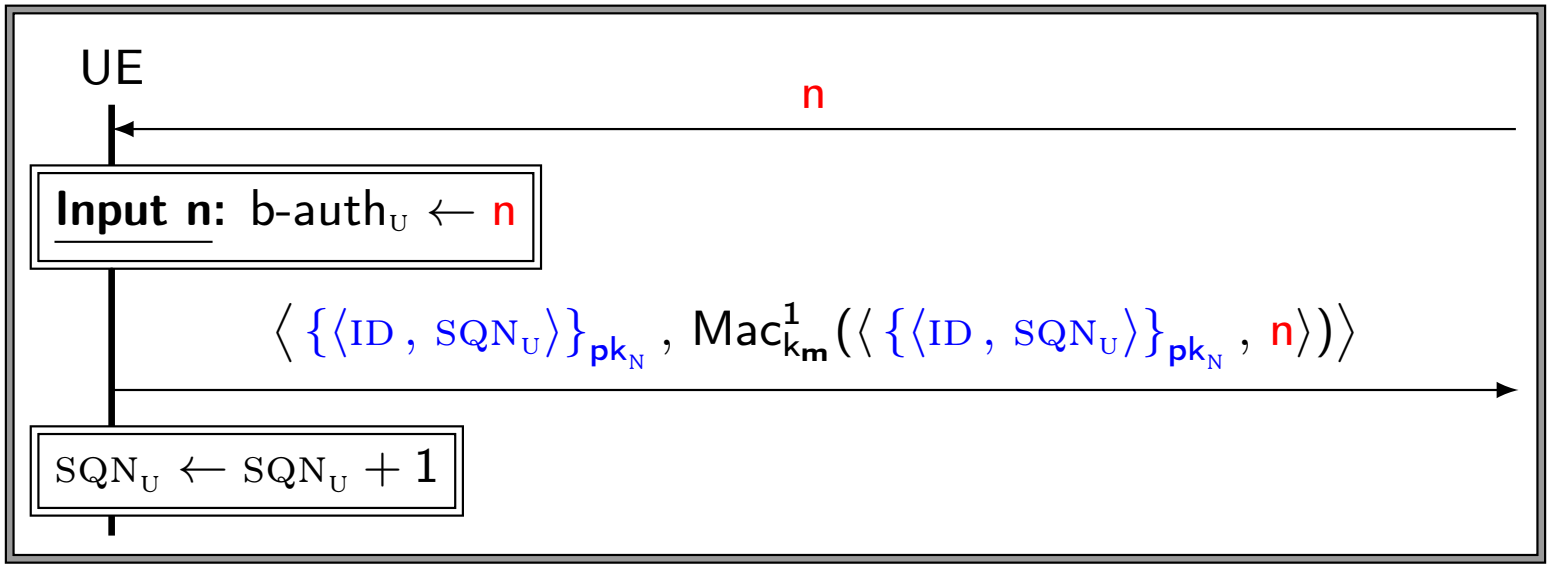

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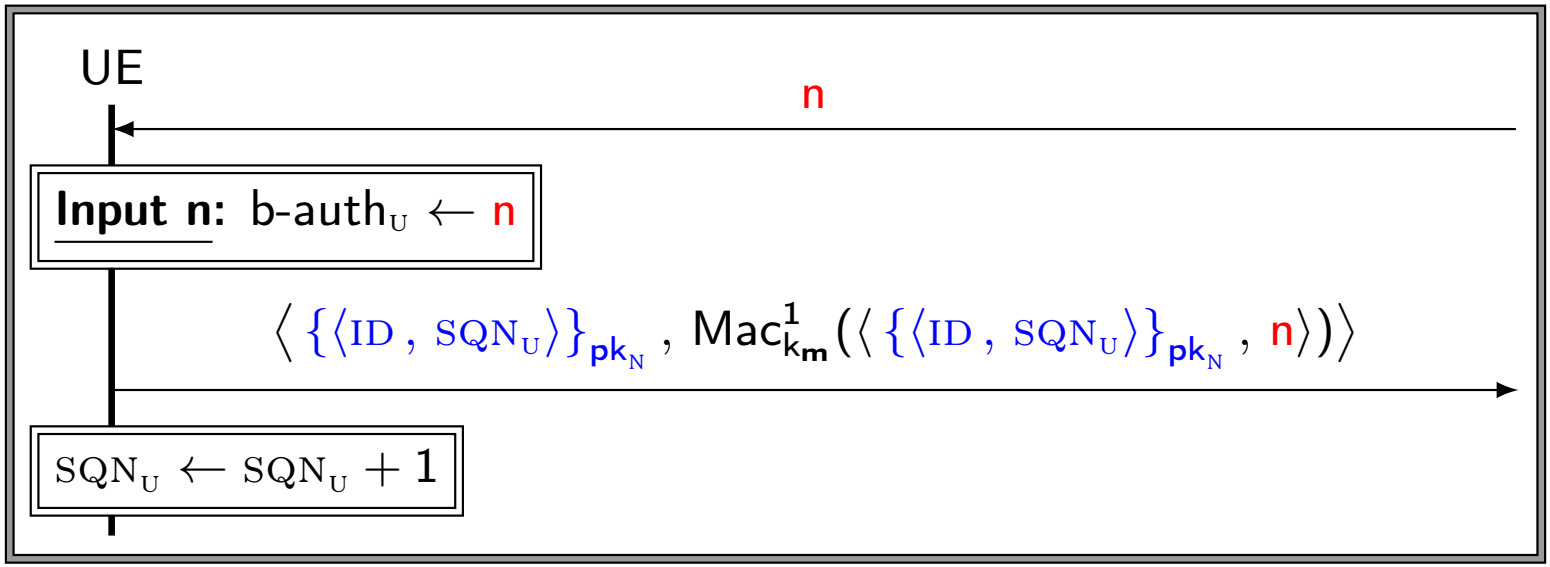

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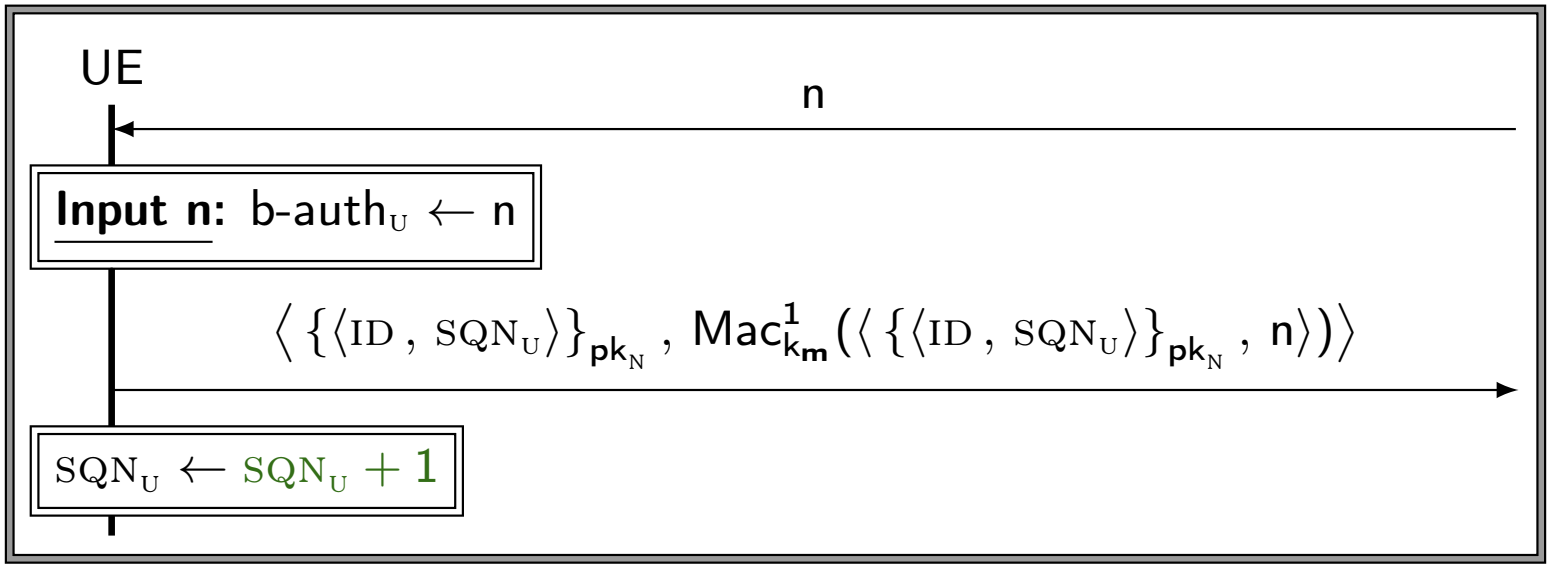

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If Mac is an EUF-MAC function, then the following axiom is valid:

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Inference Rules

Function Application

If you cannot distinguish the arguments, you cannot distinguish the images.

$$\frac{x_1, \ldots, x_n \sim y_1, \ldots, y_n}{f(x_1, \ldots, x_n) \sim f(y_1, \ldots, y_n)}\ \mathsf{FA}$$

Theorem

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Theorem

*The AKA^+ protocol is σ-unlinkable for **an arbitrary number of agents and sessions** when:*

- *The asymmetric encryption $\{\_\}_\_$ is IND-CCA1.*
- *H and H^r (resp. Mac^1–Mac^5) satisfy jointly the PRF assumption.*

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$$\begin{array}{l} \text{if } \sigma_\tau(\mathrm{sync}_{\mathrm{U}}^{\mathrm{ID}}) \\ \quad \text{then } \sigma_\tau(\mathrm{SQN}_{\mathrm{U}}^{\mathrm{ID}}) - \sigma_\tau(\mathrm{SQN}_{\mathrm{N}}^{\mathrm{ID}}) \\ \quad \text{else } \bot \end{array} \sim \begin{array}{l} \text{if } \sigma_{\underline{\tau}}(\mathrm{sync}_{\mathrm{U}}^{\mathrm{ID}_{\underline{\tau}}}) \\ \quad \text{then } \sigma_{\underline{\tau}}(\mathrm{SQN}_{\mathrm{U}}^{\mathrm{ID}_{\underline{\tau}}}) - \sigma_{\underline{\tau}}(\mathrm{SQN}_{\mathrm{N}}^{\mathrm{ID}_{\underline{\tau}}}) \\ \quad \text{else } \bot \end{array}$$

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- We defined the notion of σ-unlinkability.
- We proved in the BC logic that AKA$^+$ is σ-unlinkability.
- We also proved that AKA$^+$ provides mutual authentication.

Thanks for your attention

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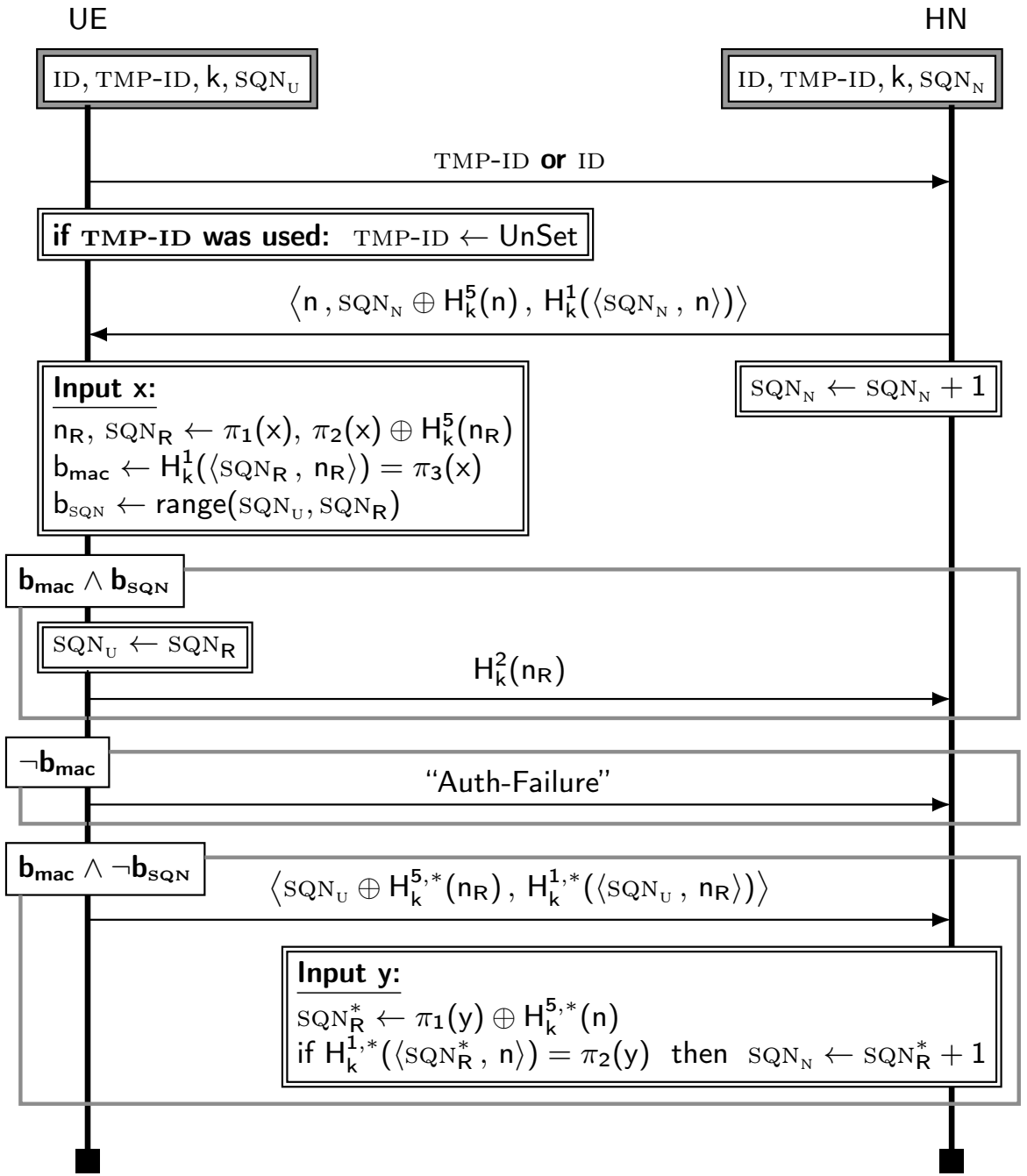
No Pre-Fetching of Authentication Vectors

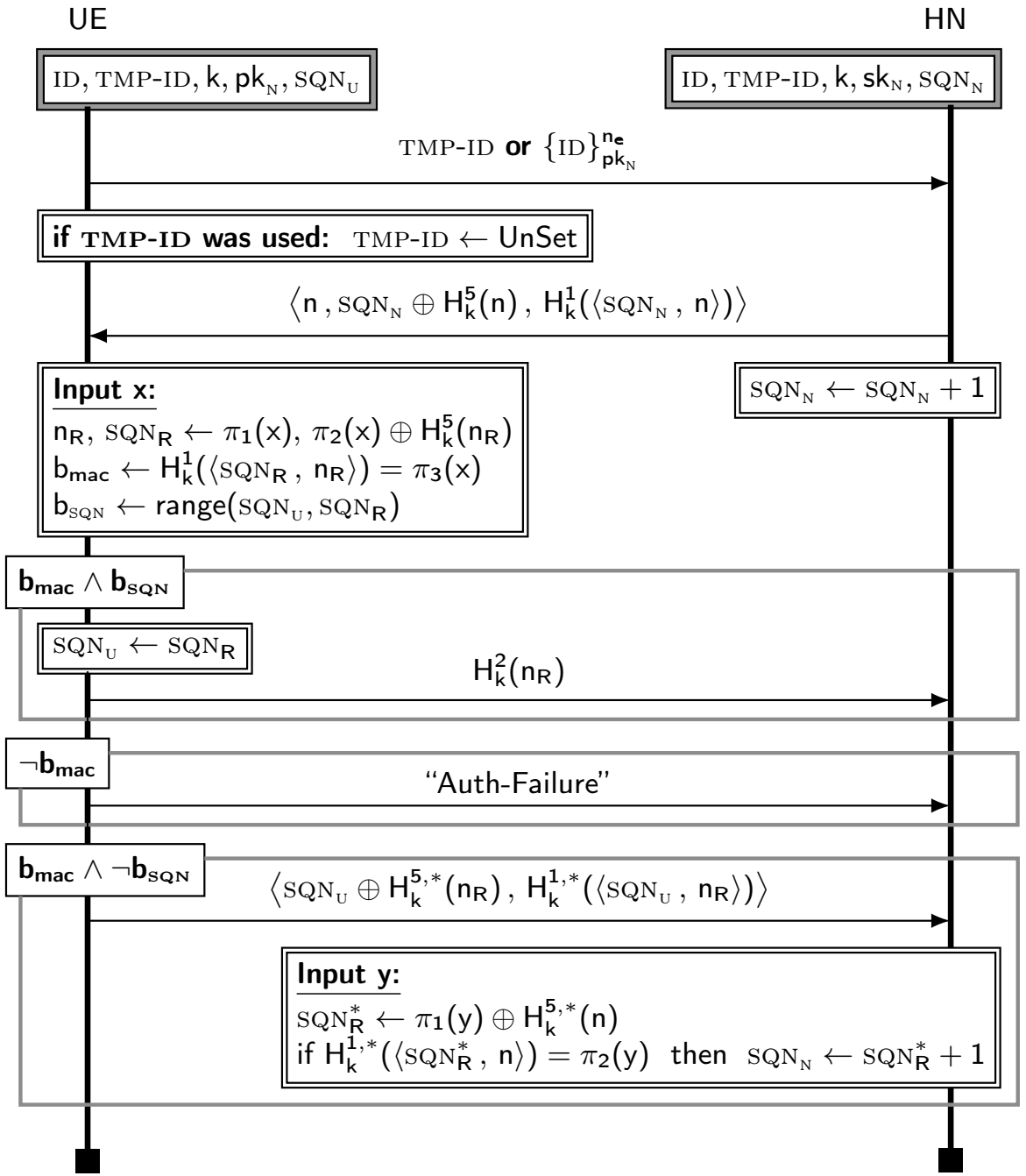
From the 3GPP specification for 5G-AKA ([3GPP, 2018], p. 37)

5G AKA does not support requesting multiple 5G AVs, neither the SEAF pre-fetching 5G AVs from the home network for future use.

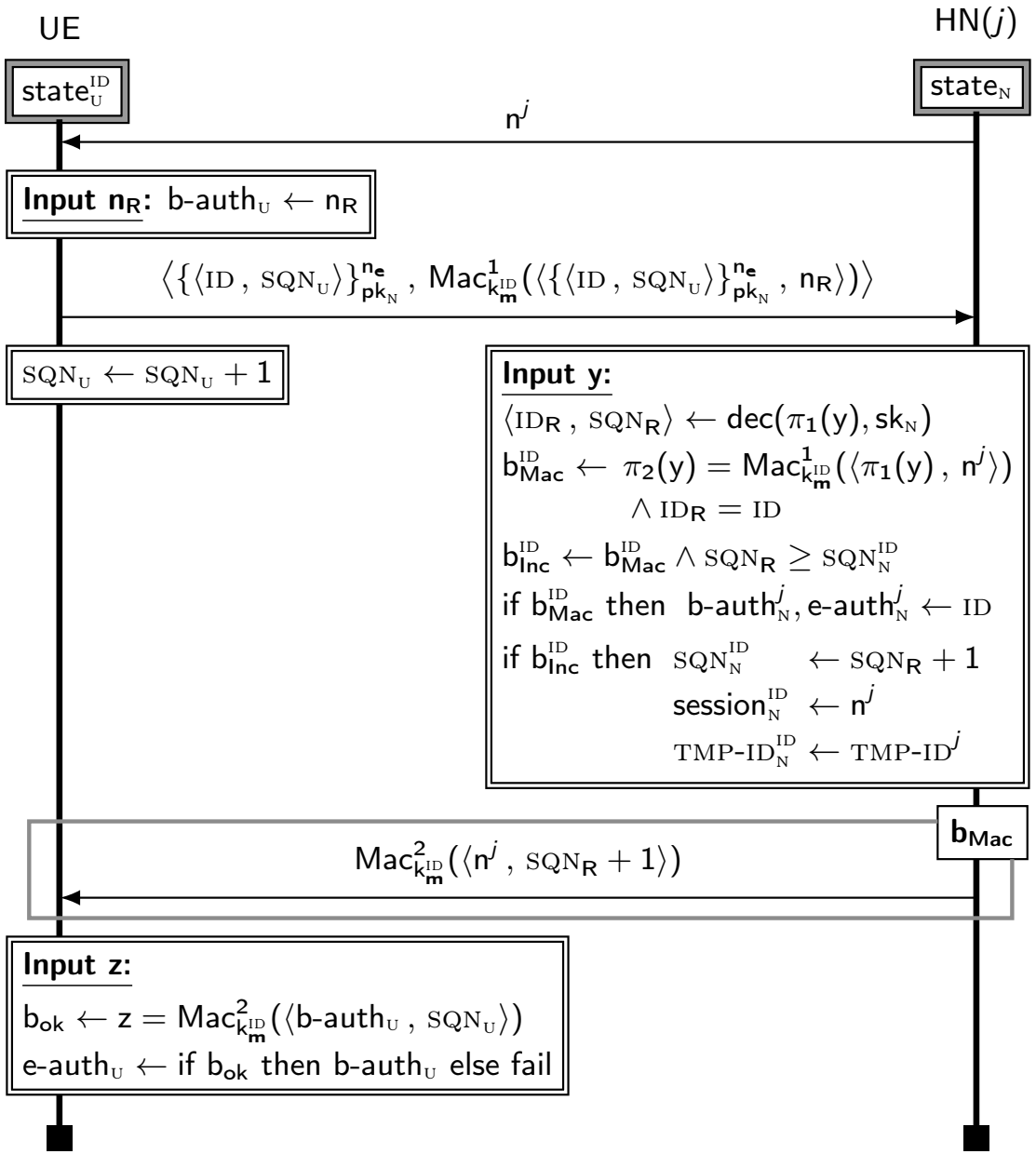
4G-AKA


UE
HN
ID, TMP-ID, k, SQN_U
ID, TMP-ID, k, SQN_N
TMP-ID or ID
if TMP-ID was used: TMP-ID ← UnSet
⟨n , SQN_N ⊕ H^5_k(n) , H^1_k(⟨SQN_N , n⟩)⟩
Input x:
n_R, SQN_R ← π_1(x), π_2(x) ⊕ H^5_k(n_R)
b_mac ← H^1_k(⟨SQN_R , n_R⟩) = π_3(x)
b_SQN ← range(SQN_U, SQN_R)
SQN_N ← SQN_N + 1
b_mac ∧ b_SQN
SQN_U ← SQN_R
H^2_k(n_R)
¬b_mac
"Auth-Failure"
b_mac ∧ ¬b_SQN
⟨SQN_U ⊕ H^{5,*}_k(n_R) , H^{1,*}_k(⟨SQN_U , n_R⟩)⟩
Input y:
SQN*_R ← π_1(y) ⊕ H^{5,*}_k(n)
if H^{1,*}_k(⟨SQN*_R , n⟩) = π_2(y) then SQN_N ← SQN*_R + 1

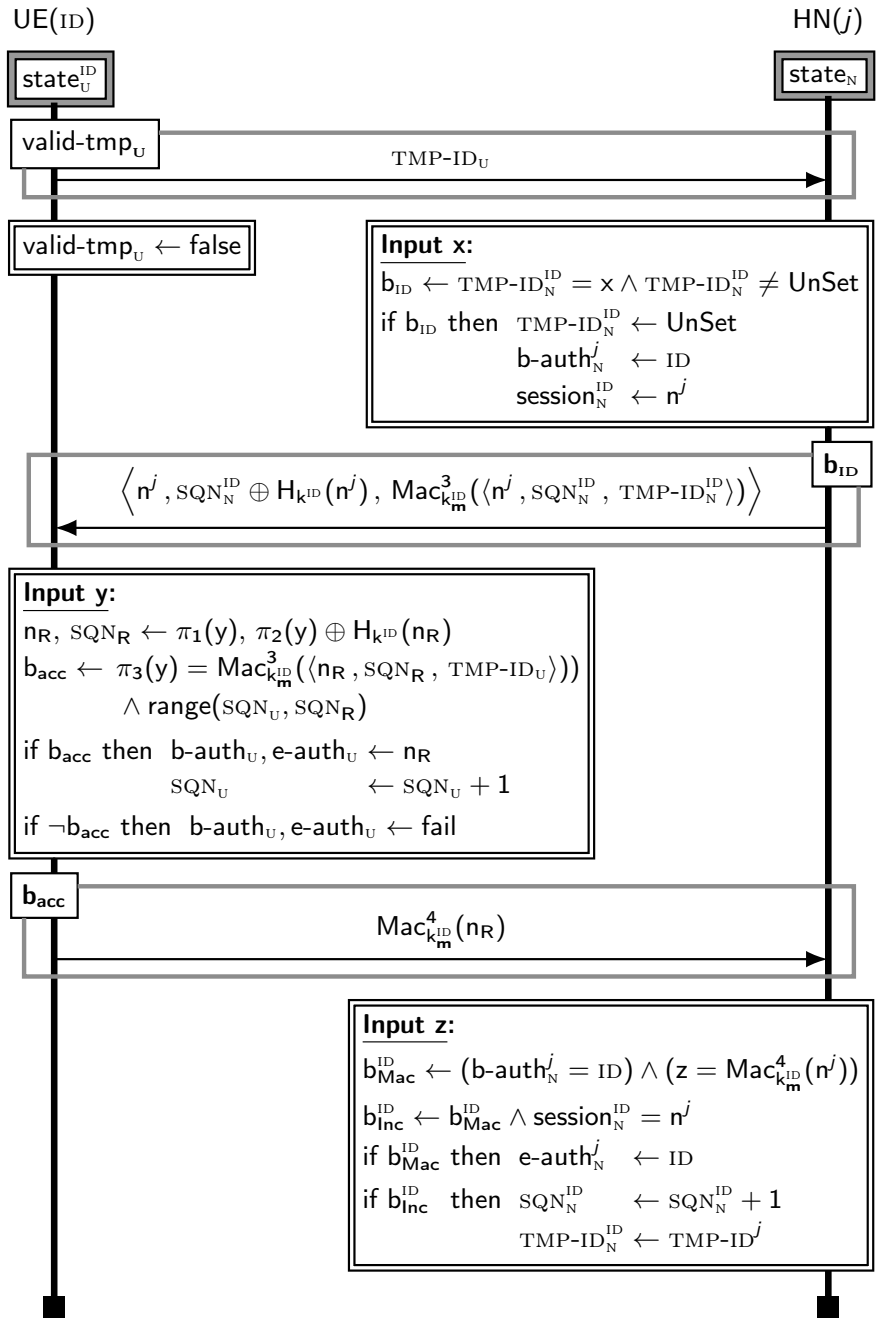
5G-AKA


UE
HN
$\mathrm{ID}, \mathrm{TMP\text{-}ID}, \mathsf{k}, \mathsf{pk}_N, \mathrm{SQN}_U$
$\mathrm{ID}, \mathrm{TMP\text{-}ID}, \mathsf{k}, \mathsf{sk}_N, \mathrm{SQN}_N$
$\mathrm{TMP\text{-}ID}$ **or** $\{\mathrm{ID}\}^{\mathsf{ne}}_{\mathsf{pk}_N}$
if TMP-ID was used: $\mathrm{TMP\text{-}ID} \leftarrow \mathsf{UnSet}$
$\langle \mathsf{n}, \mathrm{SQN}_N \oplus \mathsf{H}^5_\mathsf{k}(\mathsf{n}), \mathsf{H}^1_\mathsf{k}(\langle \mathrm{SQN}_N, \mathsf{n} \rangle) \rangle$
Input x:
$\mathsf{n}_R, \mathrm{SQN}_R \leftarrow \pi_1(\mathsf{x}), \pi_2(\mathsf{x}) \oplus \mathsf{H}^5_\mathsf{k}(\mathsf{n}_R)$
$\mathsf{b}_{\mathsf{mac}} \leftarrow \mathsf{H}^1_\mathsf{k}(\langle \mathrm{SQN}_R, \mathsf{n}_R \rangle) = \pi_3(\mathsf{x})$
$\mathsf{b}_{\mathrm{SQN}} \leftarrow \mathsf{range}(\mathrm{SQN}_U, \mathrm{SQN}_R)$
$\mathrm{SQN}_N \leftarrow \mathrm{SQN}_N + 1$
$\mathsf{b}_{\mathsf{mac}} \wedge \mathsf{b}_{\mathrm{SQN}}$
$\mathrm{SQN}_U \leftarrow \mathrm{SQN}_R$
$\mathsf{H}^2_\mathsf{k}(\mathsf{n}_R)$
$\neg \mathsf{b}_{\mathsf{mac}}$
"Auth-Failure"
$\mathsf{b}_{\mathsf{mac}} \wedge \neg \mathsf{b}_{\mathrm{SQN}}$
$\langle \mathrm{SQN}_U \oplus \mathsf{H}^{5,*}_\mathsf{k}(\mathsf{n}_R), \mathsf{H}^{1,*}_\mathsf{k}(\langle \mathrm{SQN}_U, \mathsf{n}_R \rangle) \rangle$
Input y:
$\mathrm{SQN}^*_R \leftarrow \pi_1(\mathsf{y}) \oplus \mathsf{H}^{5,*}_\mathsf{k}(\mathsf{n})$
if $\mathsf{H}^{1,*}_\mathsf{k}(\langle \mathrm{SQN}^*_R, \mathsf{n} \rangle) = \pi_2(\mathsf{y})$ then $\mathrm{SQN}_N \leftarrow \mathrm{SQN}^*_R + 1$

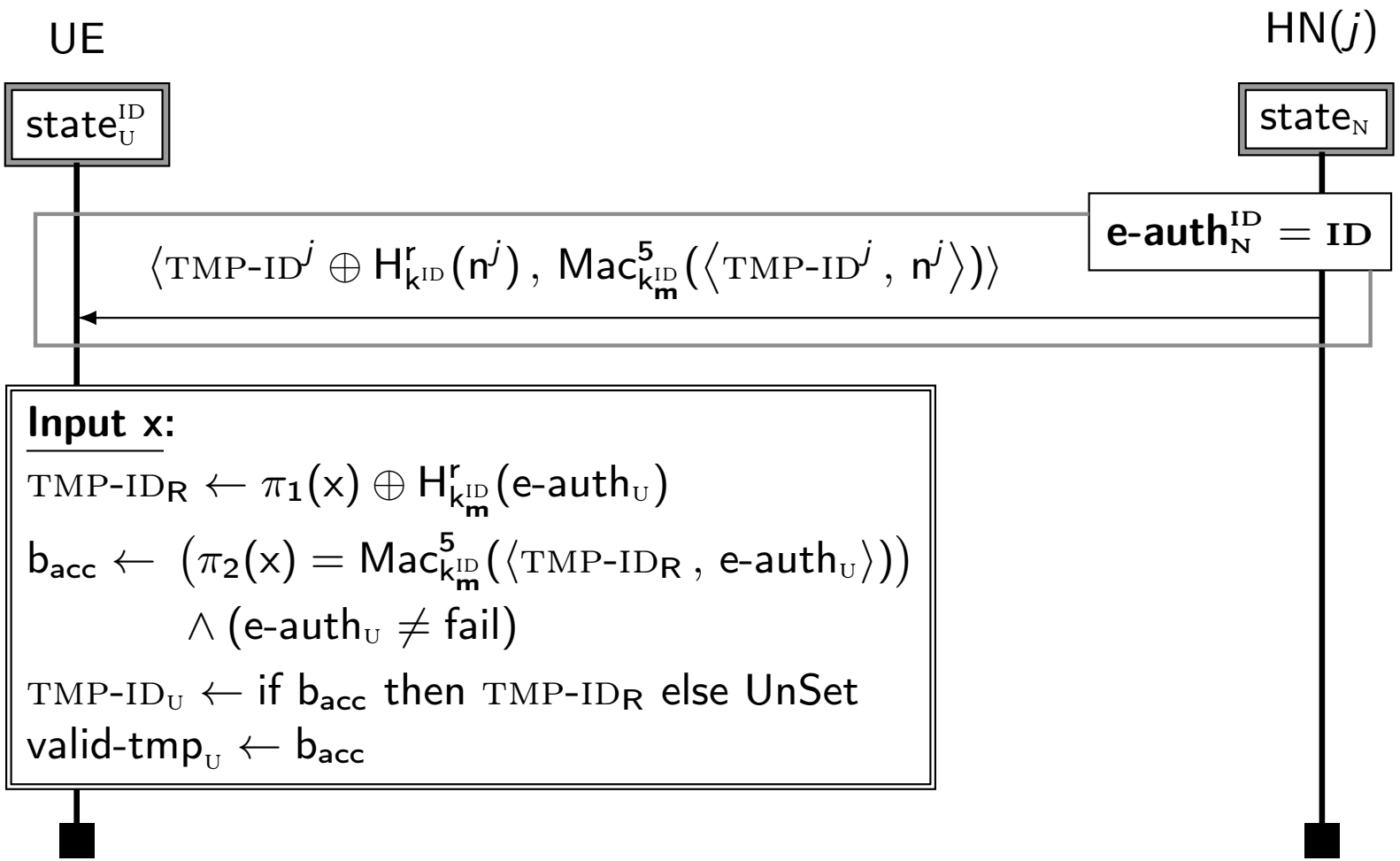
ID
Sub-Protocol



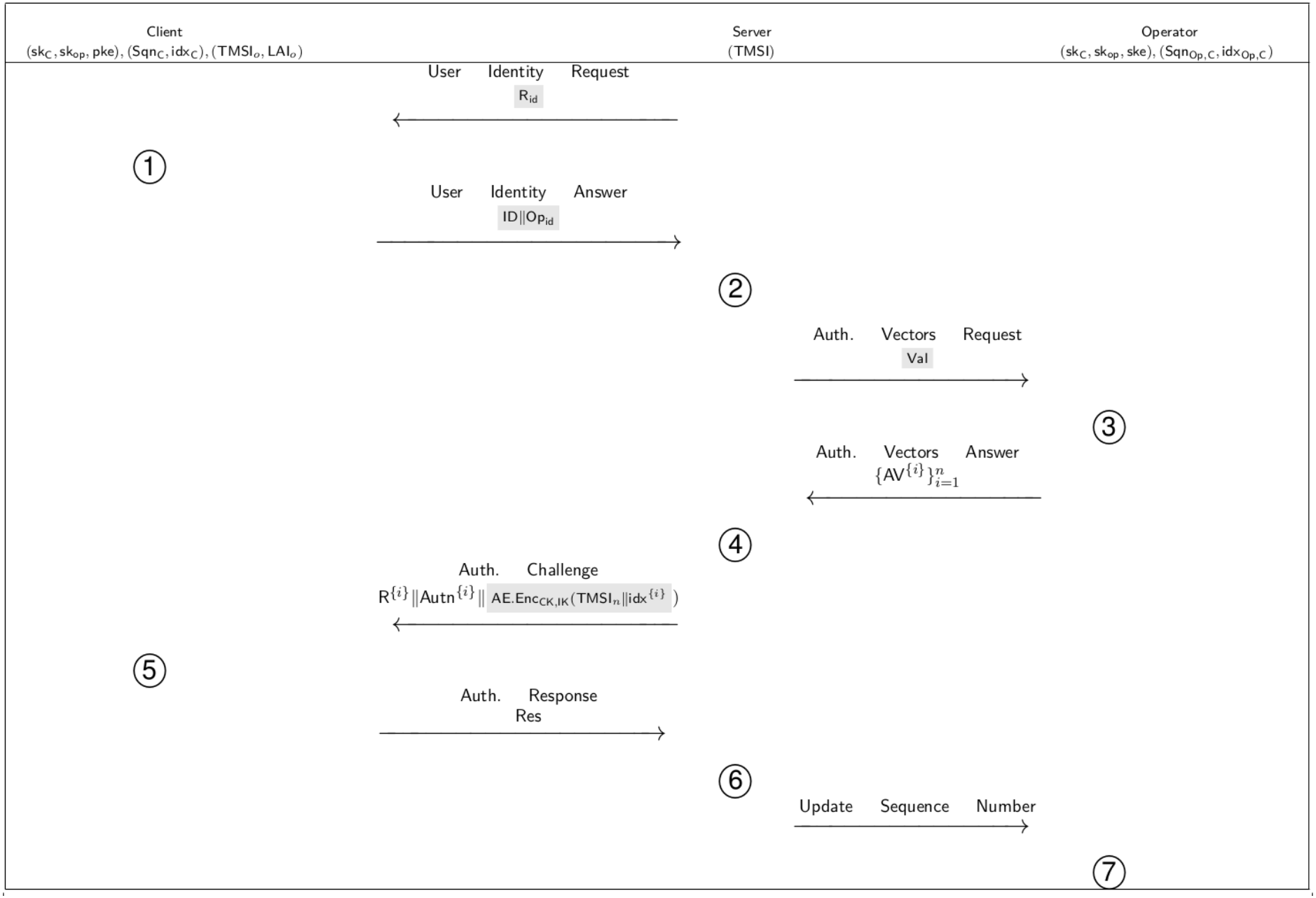
TMP-ID
Sub-Protocol



The ASSIGN-TMP-ID Sub-Protocol



PRIV-AKA [Fouque et al., 2016]



PRIV-AKA [Fouque et al., 2016]

Client	Server	Operator
①: Compute the identifier: If $\text{flag}_{\text{TMSI}} := 0$ then ID = TMSI. Else, $\text{ID} = \text{PKE.Enc}_{\text{pke}}(f_5(\text{keys}, \text{R}_{\text{id}}, \text{IMSI}, \text{idx}_\text{C}) \| \text{R}_{\text{id}} \| \text{IMSI} \| \text{idx}_\text{C})$. $\text{flag}_{\text{TMSI}} := 1$.		③: Verify the identity of the client with Val. If this holds, retrieve idx_C, set $\text{idx}_{\text{Op,C}} := \text{idx}_\text{C}$ Generate $(\text{R}^{\{1\}}, ..., \text{R}^{\{n\}})$. Denote: $\text{keys} := (\text{sk}_\text{C}, \text{sk}_{\text{op}})$. For each $i = 1, \ldots, n$, compute: $\text{Mac}_\text{S} \leftarrow \mathcal{F}_1(\text{keys}, \text{R}^{\{i\}}, \text{Sqn}^{\{i\}}, \text{Res}_\text{S}, \text{AMF})$, $\text{Mac}_\text{C} \leftarrow \mathcal{F}_1^*(\text{keys}, \text{R}^{\{i\}}, \text{Sqn}^{\{i\}}, \text{Res}_\text{S}, \text{AMF})$, $\text{CK} \leftarrow \mathcal{F}_3(\text{keys}, \text{R}^{\{i\}}, \text{Sqn}^{\{i\}}, \text{Res}_\text{S}, \text{AMF})$, $\text{IK} \leftarrow \mathcal{F}_4(\text{keys}, \text{R}^{\{i\}}, \text{Sqn}^{\{i\}}, \text{Res}_\text{S}, \text{AMF})$, $\text{AK} \leftarrow \mathcal{F}_5(\text{keys}, \text{R}^{\{i\}}, \text{Res}_\text{S})$, $\text{Autn}^{\{i\}} \leftarrow (\text{Sqn}^{\{i\}} \oplus \text{AK}) \| \text{AMF} \| \text{Mac}_\text{S}$, $\text{Sqn}^{\{i\}} \leftarrow \text{inc}(\text{Sqn}^{\{i-1\}})$, $\text{AV}^{\{i\}} := (\text{R}^{\{i\}}, \text{CK}, \text{IK}, \text{Autn}^{\{i\}}, \text{Mac}_\text{C}, \text{idx}^{\{i\}})$, with $\text{Sqn}^{\{1\}} := \text{Sqn}_{\text{Op,C}}$, $\text{idx}^{\{1\}} := \text{idx}_{\text{Op,C}}$, $\forall i \neq 1, \text{idx}^{\{i\}} = 0$. End for.
⑤: Compute AK using $\text{R}^{\{i\}}$. Recover $\text{Sqn}^{\{i\}}$ (from AK). Check Mac_S value. Compute: IK, CK; Retrieve the received index and the new TMSI. If abort caused or the AE does not verify, set $\text{flag}_{\text{TMSI}} := 1$ and increment: $\text{idx}_\text{C} := \text{idx}_\text{C} + 1$. Else, check validity of $\text{Sqn}^{\{i\}}$, i.e if one of the following conditions is correct: – $\text{Sqn}_\text{C} = \text{Sqn}^{\{i\}}$. – $\text{Sqn}_\text{C} = \text{inc}(\text{Sqn}^{\{i\}})$ and $\text{idx}^{\{i\}} = \text{idx}_\text{C} + 1$. If the first condition is accepted: reset the index idx_C, update the sequence number $\text{Sqn}_\text{C} = \text{inc}(\text{Sqn}_\text{C})$. If the second condition is accepted: $\text{idx}_\text{C}=\text{idx}_\text{C}+1$. Compute $\text{Res} := \mathcal{F}_1^*(\text{keys}, \text{R}^{\{i\}}, \text{Sqn}^{\{i\}}, \text{Res}_\text{S}, \text{AMF})$. Update the internal index. Allocate the new TMSI. $\text{flag}_{\text{TMSI}} := 0$.	②: Process the identifier ID: If the identifier is a TMSI then Val = IMSI. Otherwise, $\text{Val} = (\text{ID}, \text{R}_{\text{id}})$. ④: Store $\{\text{AV}^{\{i\}}\}_{i=1}^n$. Choose $\text{AV}^{\{i\}}$ one by one in order. Then, it sends the authentication challenge and the new couple $(\text{TMSI}_n, \text{idx}^{\{i\}})$ encrypted and authenticated by the session keys. ⑥: If the authentication of the client is verified ($\text{Res} \stackrel{?}{=} \text{Mac}_\text{C}$), then they ask to the server the update of its sequence number. Otherwise, the protocol is aborted.	⑦: Update the sequence number: $\text{Sqn}_{\text{Op,C}} \leftarrow \text{inc}(\text{Sqn}_{\text{Op,C}})$. Reset the index $\text{idx}_{\text{Op,C}}$.

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