The 5G-AKA Authentication Protocol Privacy

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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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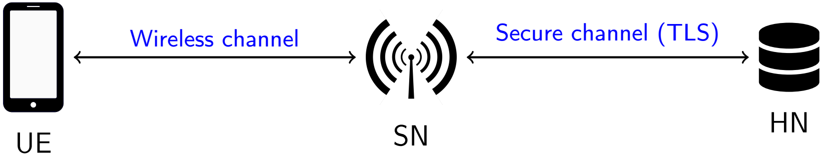

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Some security goal of AKA

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- Authentication of the antenna by the network.
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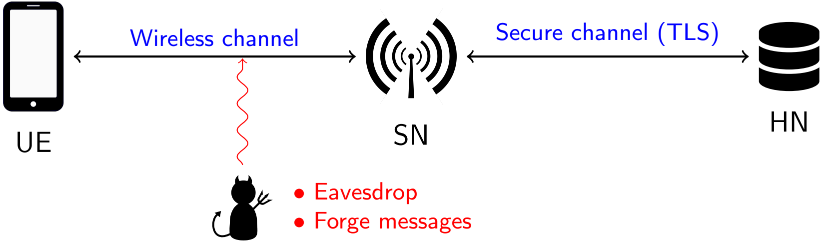
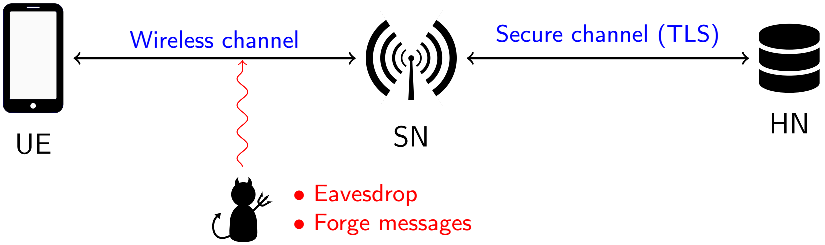


- Eavesdrop
- Forge messages

Protocol Modeling



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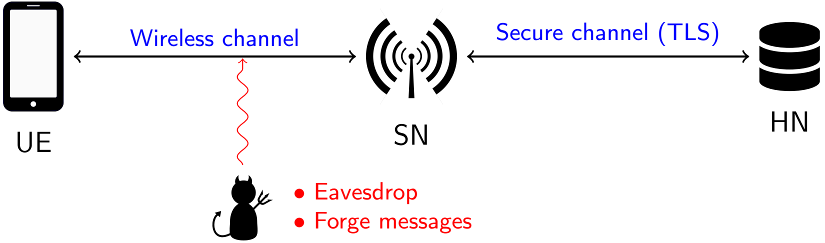

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⟹ We do not model the antenna: we have a two party protocol.

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Cryptographic Primitives

- Asymmetric encryption requires randomness.

⇒ 4G-AKA uses only symmetric one-way functions.

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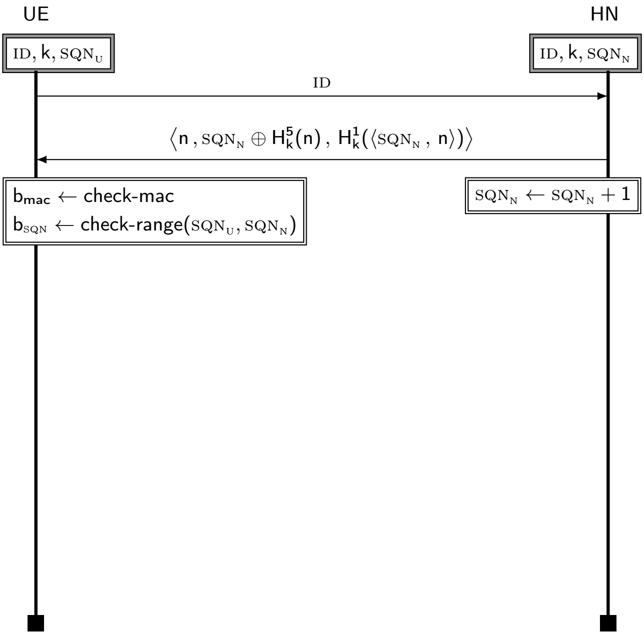
Authentication protocols need to prevent message replays. In 4G-AKA:

- 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 (SQN_U and SQN_N).
  - ⇒ De-synchronization possible.

4G-AKA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HN
ID, k, SQN_U
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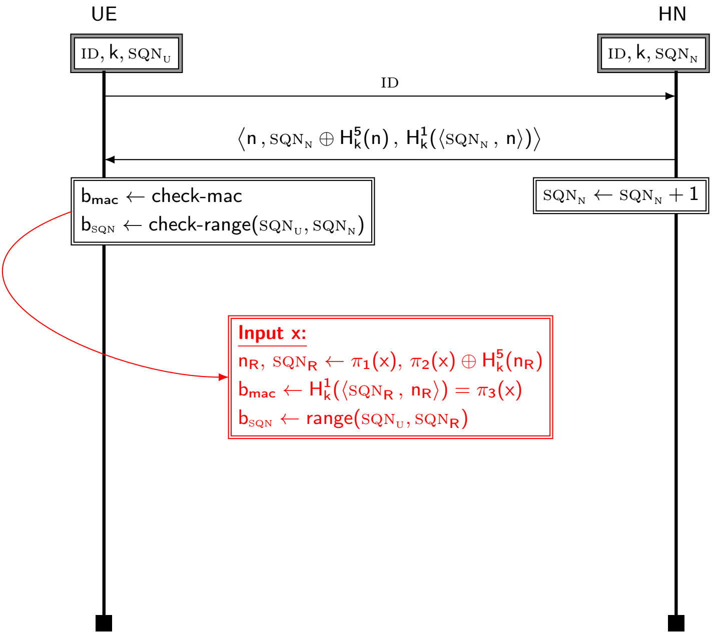
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Input x:
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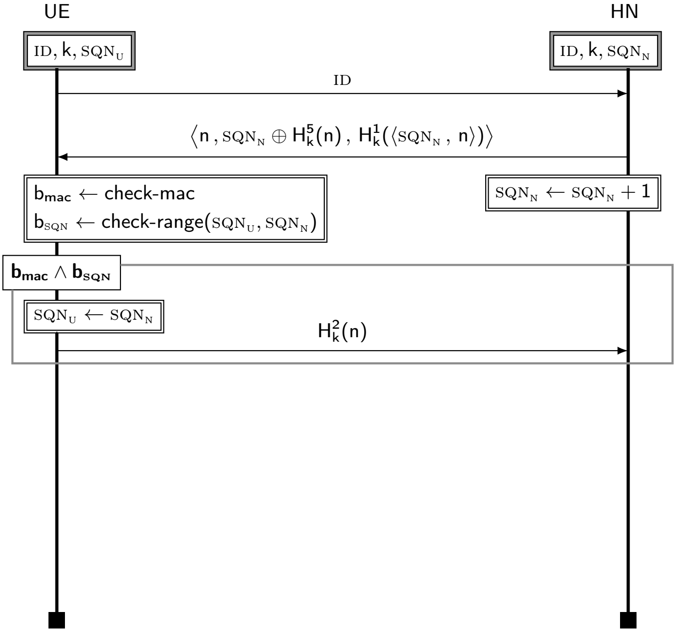
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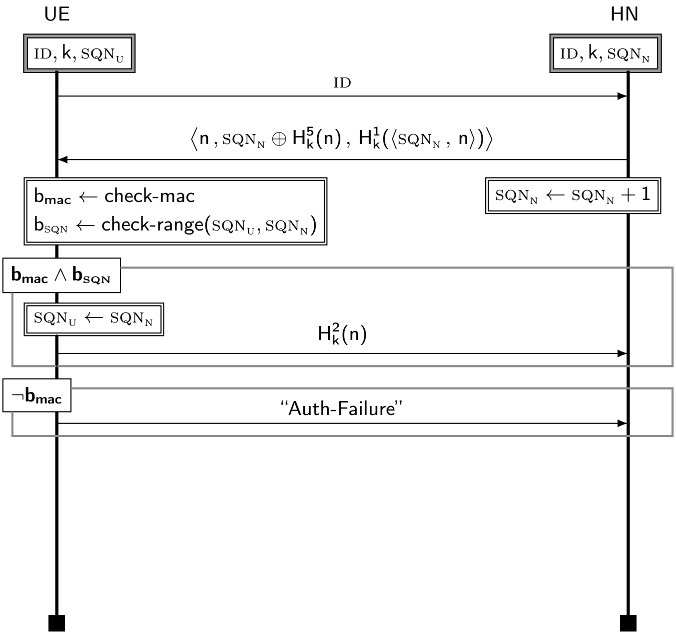

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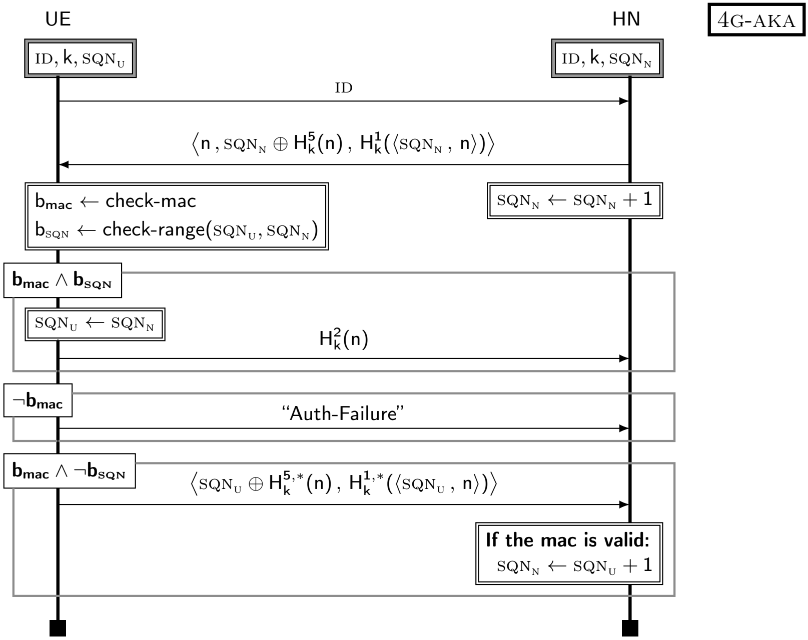
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Not confidentiality of the user identity

The ID is sent in plain text!

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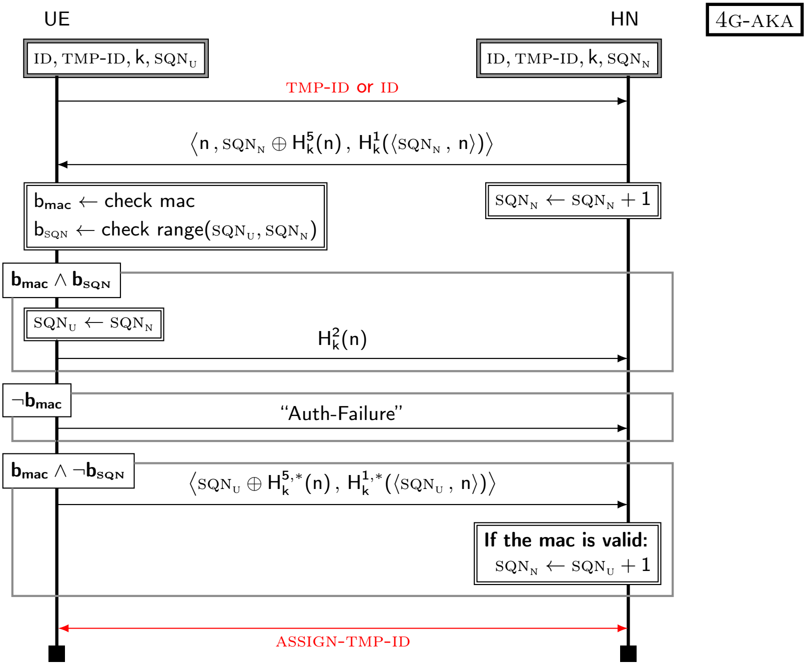
4G-AKA solution

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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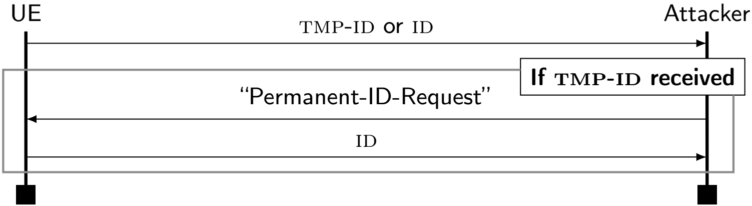
$\Longrightarrow$ This is not realistic!

The IMSI Catcher Attack [Strobel, 2007]



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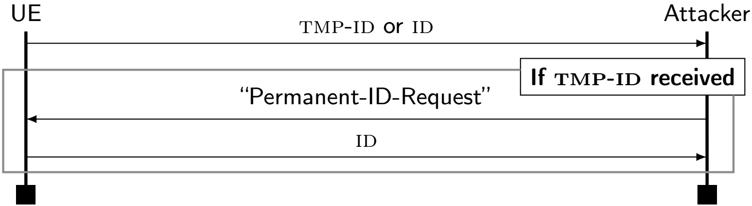

Why this is a major attack

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

Privacy in 5G-AKA

The 5G-AKA protocol

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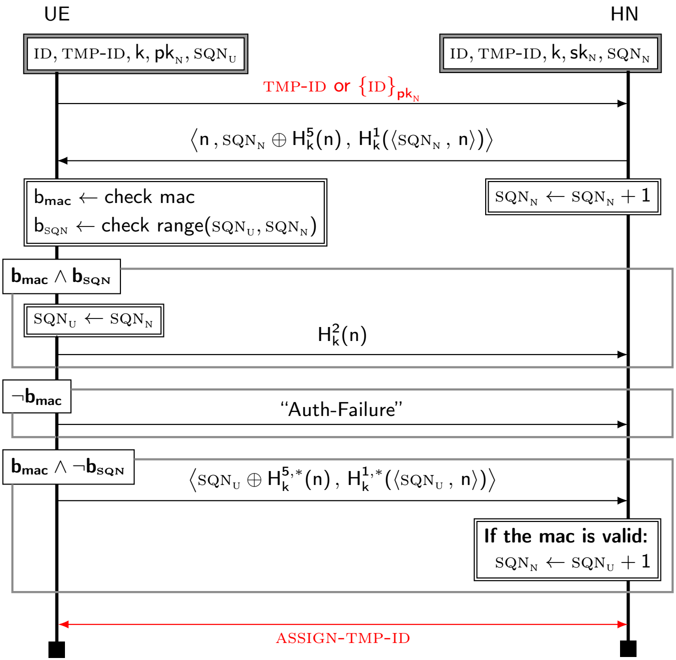
3GPP fix for 5G-AKA

Simply encrypt the permanent identity by sending $\{\mathrm{ID}\}_{\mathsf{pk}_{\mathrm{N}}}$

5G-AKA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For confidentiality of the ID, yes.

For unlinkability, no.

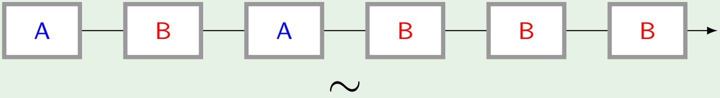
Unlinkability

Linkability Attack

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

Unlinkability

Example



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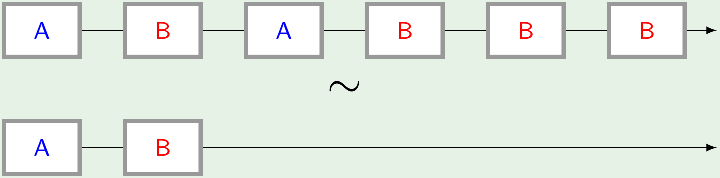

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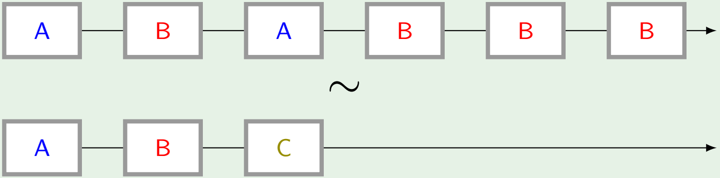

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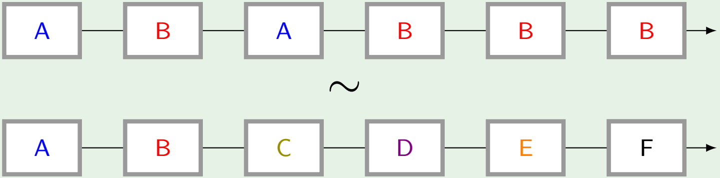

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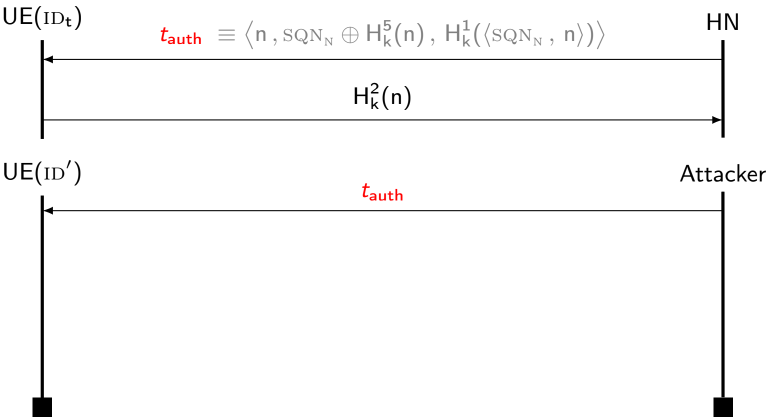

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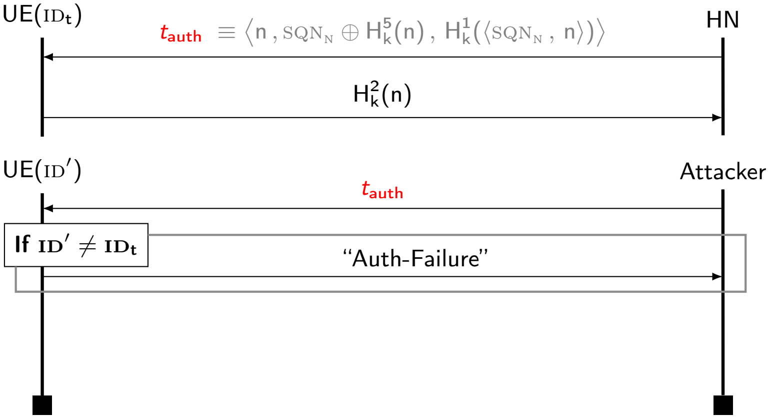

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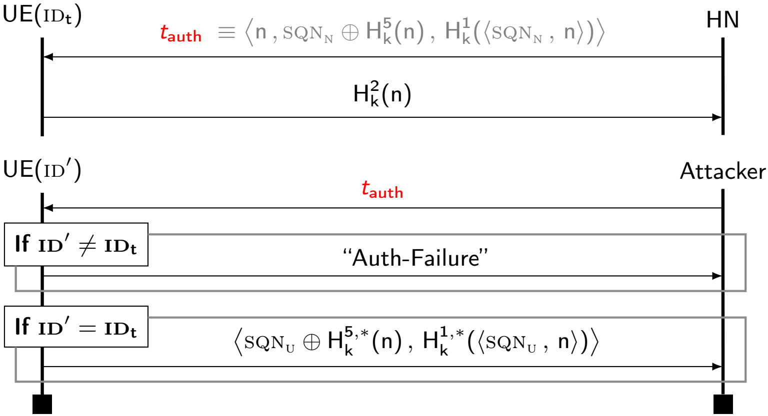

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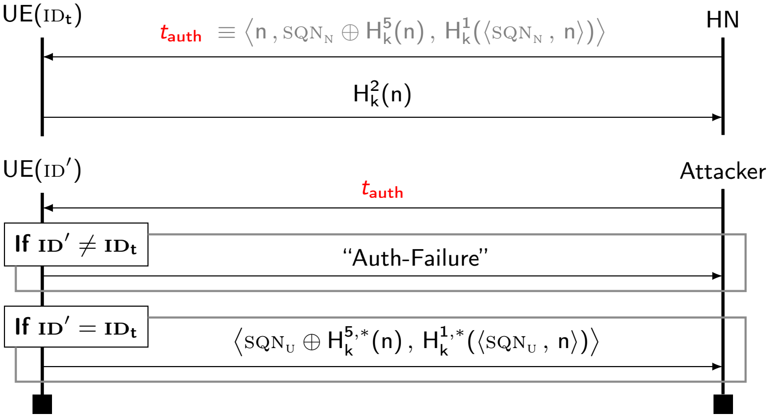

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The adversary knows if it interacted with ID$_t$ or ID$'$.

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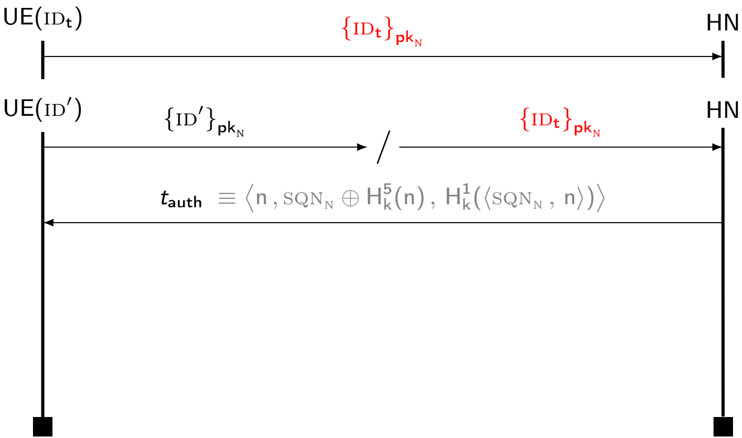

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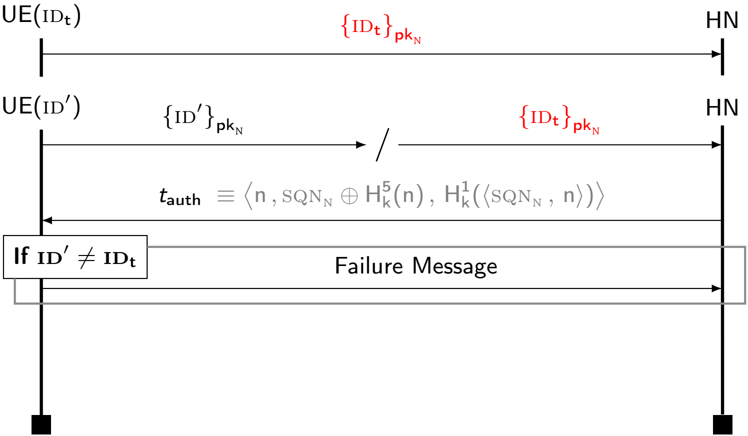

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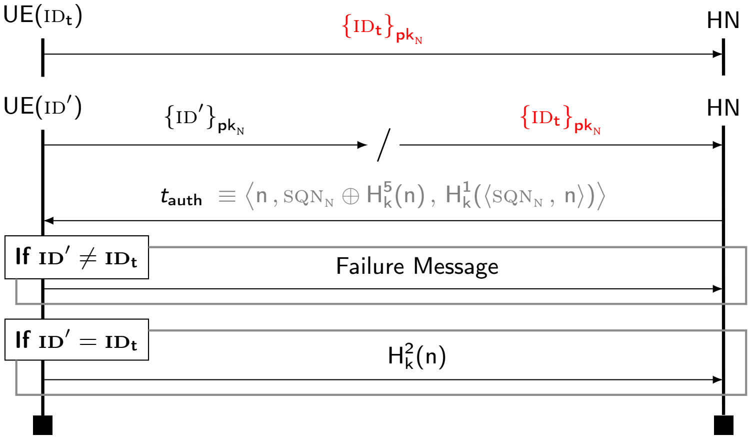

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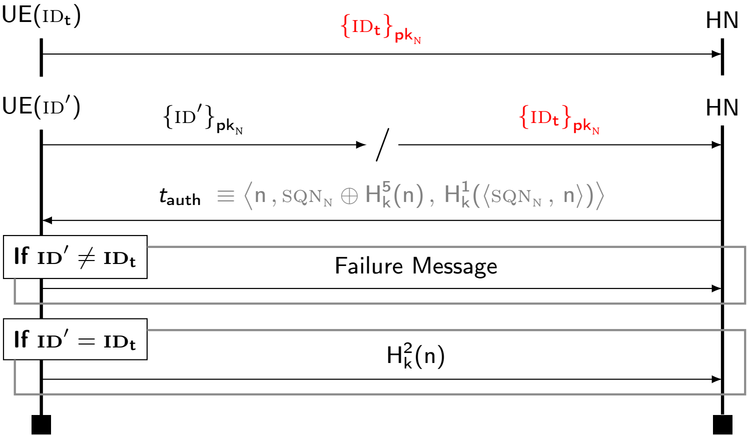

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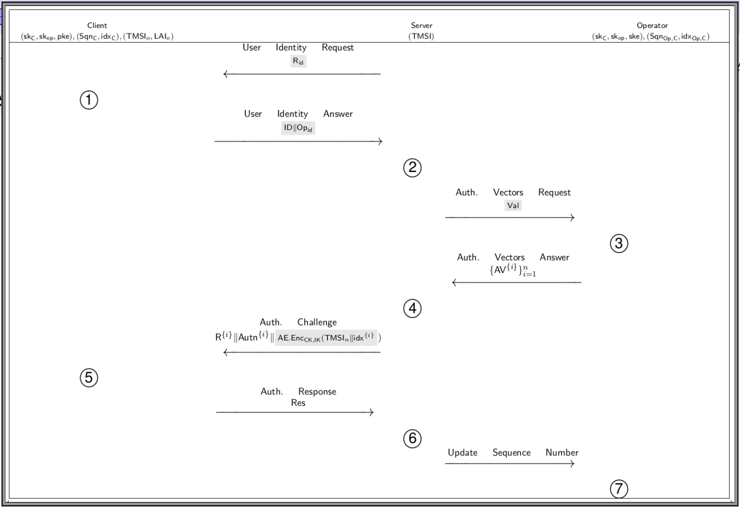

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- The user is permanently de-synchronized $\Longrightarrow$ unlinkability attack.

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- 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.

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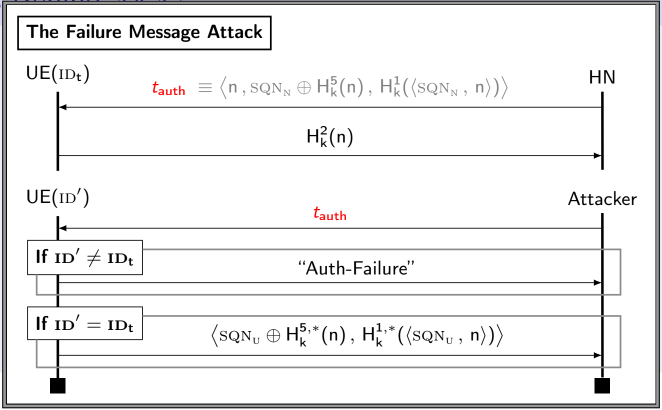

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- Postpone re-synchronization to the next session: $\{\langle \text{ID}, \text{SQN}_{\text{U}} \rangle\}_{\mathsf{pk}_{\text{N}}}$.
  - No re-synchronization message $\Longrightarrow$ no failure message attack.
  - No extra randomness for the user.

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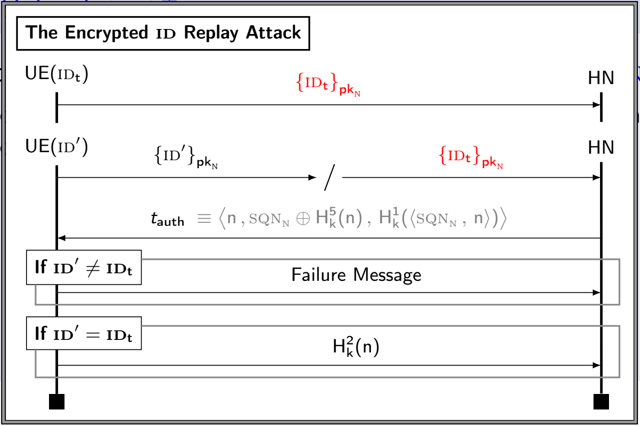

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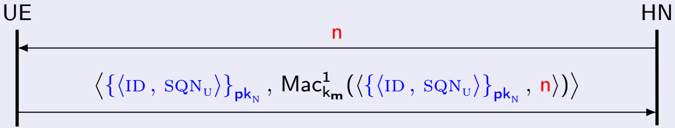
- Add a challenge n from the HN when using the permanent identity.



Architecture of AKA$^+$

AKA$^+$ Sub-Protocols

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  - is initiated by the HN with a challenge n.
  - uses the encrypted permanent identity.
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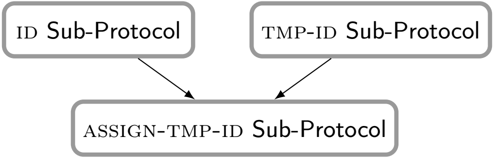
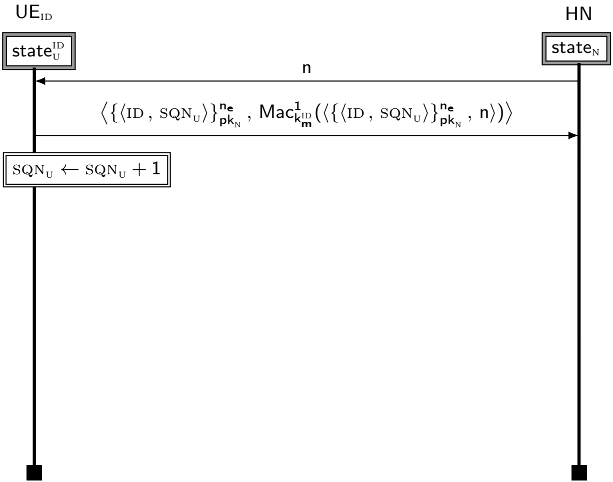
- ASSIGN-TMP-ID sub-protocol:
  - assigns a fresh temporary identity to the UE.



ID Sub-Protocol



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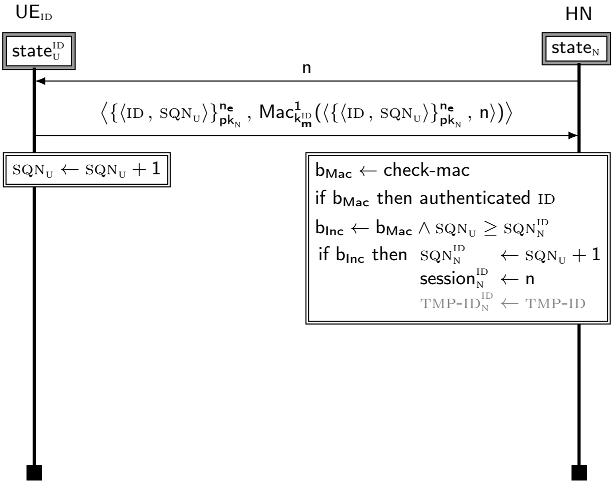

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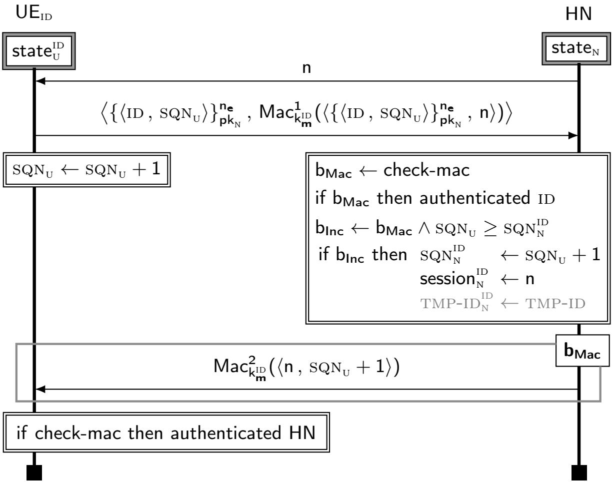
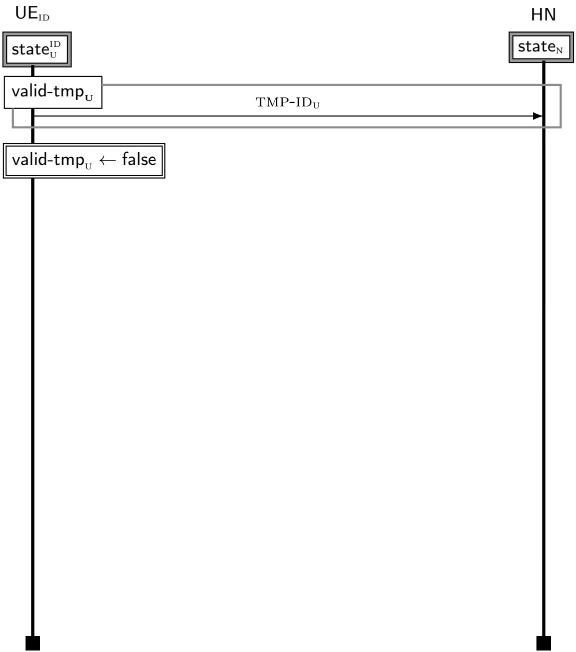


TMP-ID Sub-Protocol



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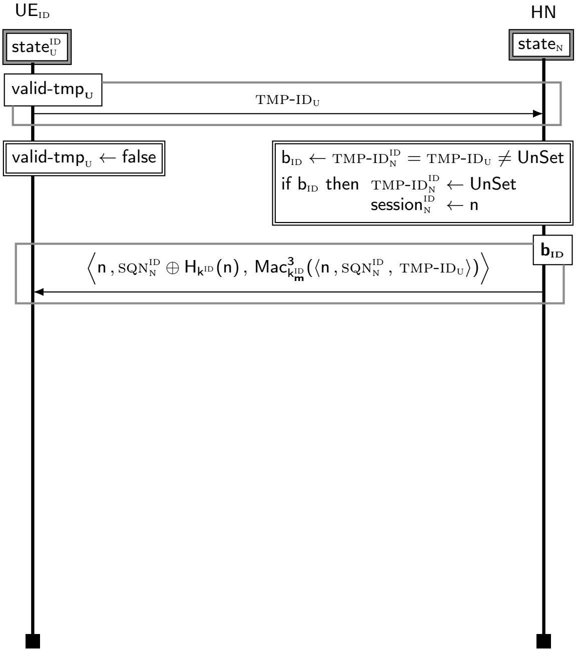

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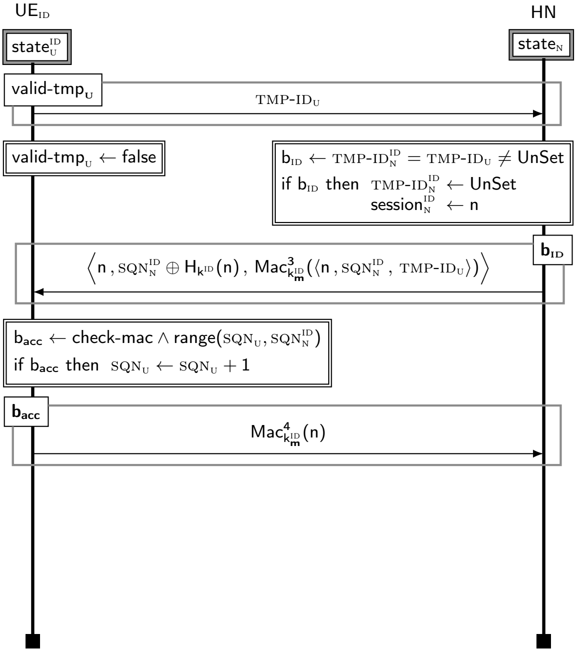

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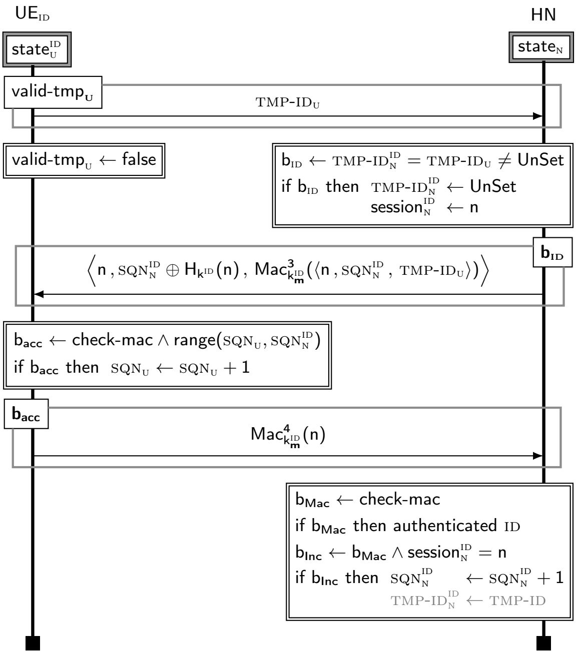
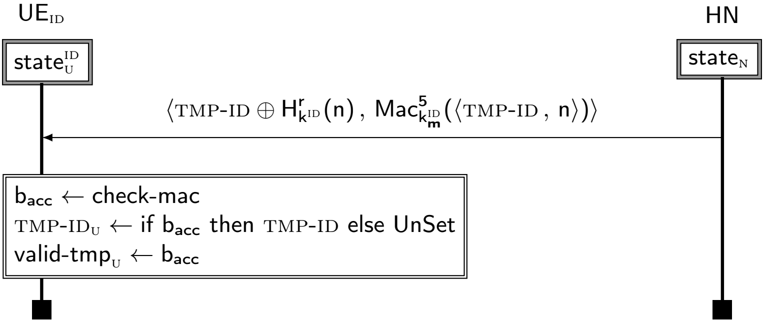


The ASSIGN-TMP-ID Sub-Protocol



Security Proofs

Objective

Formally prove that AKA^+ satisfies:

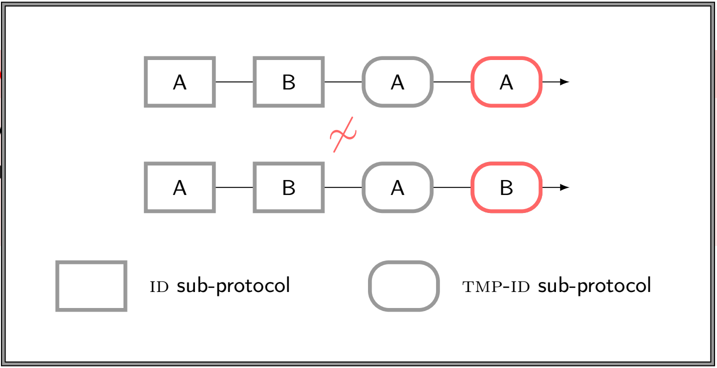
- **mutual authentication**.
- **unlinkability**.

Security Proofs

Objecti

Formally

- mu
- unl



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Formally prove that AKA^+ satisfies:

- **mutual authentication**.
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The σ-Unlinkability Property

σ-Unlinkability

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

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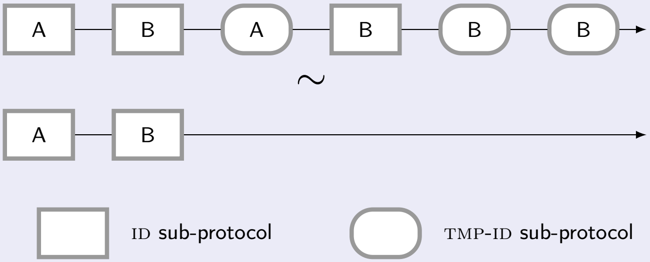
High level idea: show privacy only for a subset of the standard unlinkability game scenarios.

- 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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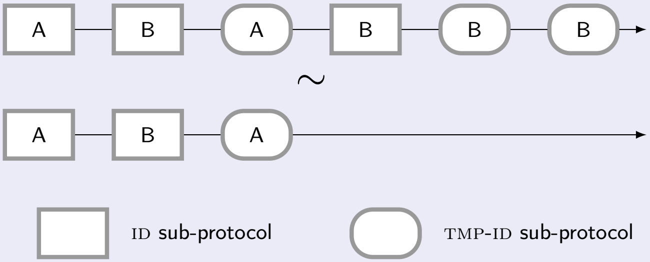

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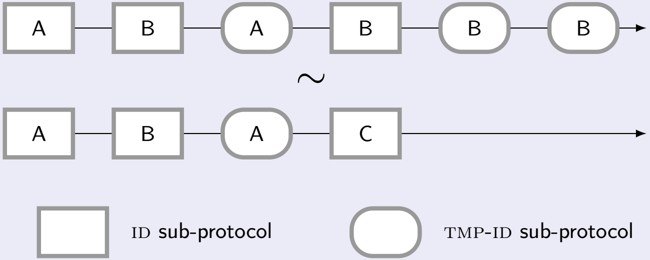

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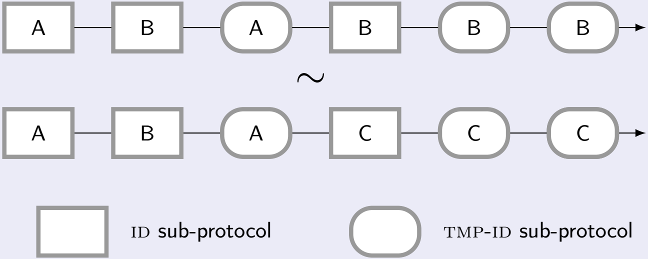

σ-Unlinkability

Efficiency vs Privacy

There is a trade-off between:

- **Efficiency:** the TMP-ID sub-protocol is faster.
- **Privacy:** the ID sub-protocol provides some privacy.

σ-Unlinkability

Efficiency vs Privacy

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- **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:

- Messages are modeled by (first-order) **terms**.

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- **Implementation assumptions** and **cryptographic hypothesis** are modeled by axioms Ax.
- We have to show that $\mathsf{Ax} \models \vec{u}_P \sim \vec{u}_Q$.

Modeling: the Protocol

Messages and State

- **Symbolic trace** of actions τ.
  Example: $\tau = \mathsf{UE}_A, \mathsf{HN}, \mathsf{UE}_B, \mathsf{UE}_A$.

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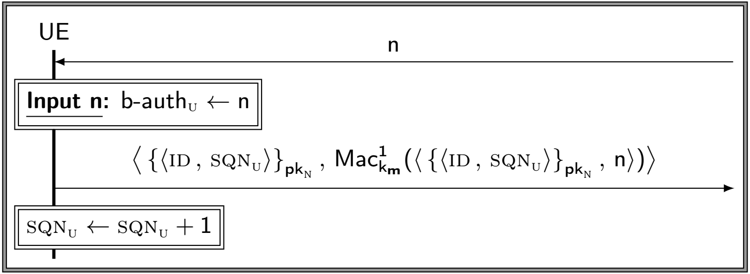
- **Symbolic trace** of actions τ.
  Example: $\tau = \mathsf{UE}_A, \mathsf{HN}, \mathsf{UE}_B, \mathsf{UE}_A$.
- **Symbolic frame** ϕ_τ: sequences of messages observed by the attacker.
- **Symbolic state** σ_τ: current state of the users and the network.

Modeling: the Protocol



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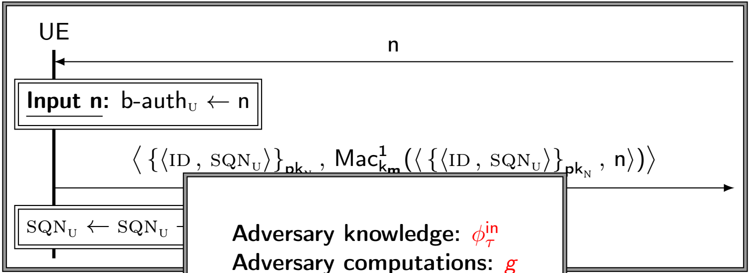
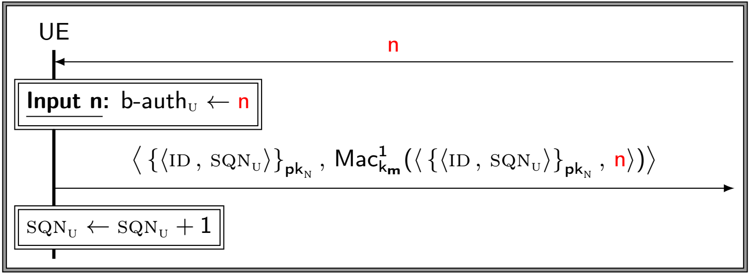


Adversary knowledge: ϕ_τ^{in}

Adversary computations: g

$\Longrightarrow$ **Symbolic input:** $g(\phi_\tau^{in})$

Modeling: the Protocol



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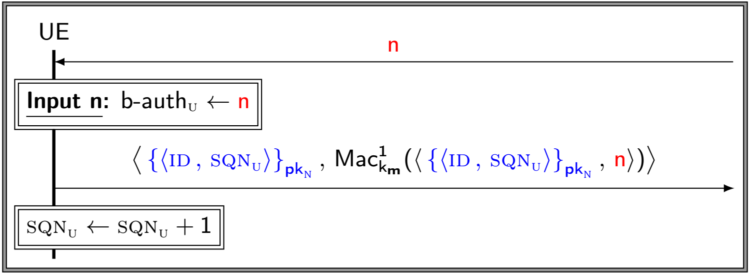

$$t_\tau^{\mathsf{enc}} \equiv \{\langle \mathrm{ID}, \sigma_\tau^{\mathsf{in}}(\mathrm{SQN_U}) \rangle\}_{\mathsf{pk_N}}^{\mathsf{n_e}}$$

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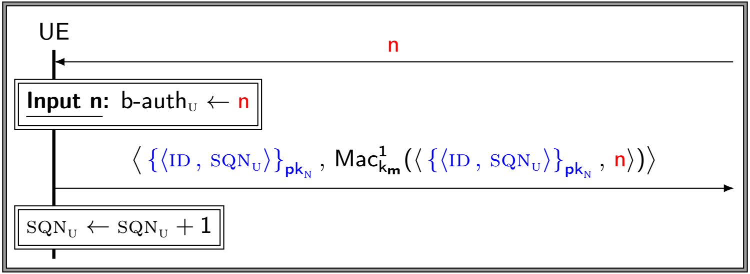

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$$\phi_\tau \equiv \phi_\tau^{\mathsf{in}}, \left\langle t_\tau^{\mathsf{enc}} , \mathsf{Mac}^1_{\mathsf{k}_\mathsf{m}^{\mathrm{ID}}}(\langle t_\tau^{\mathsf{enc}} , g(\phi_\tau^{\mathsf{in}}) \rangle) \right\rangle$$

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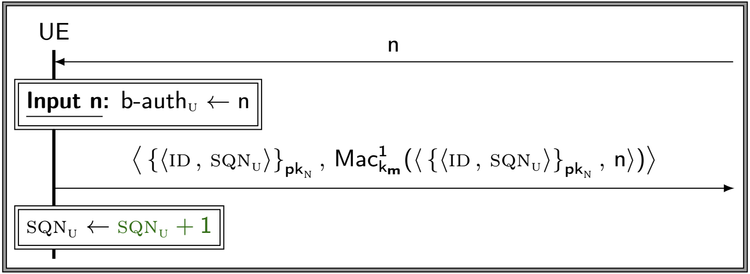

$$t^{\mathsf{enc}}_{\tau} \equiv \{\langle \mathrm{ID}, \sigma^{\mathsf{in}}_{\tau}(\mathrm{SQN_U})\rangle\}^{\mathsf{n_e}}_{\mathsf{pk_N}}$$

$$\phi_{\tau} \equiv \phi^{\mathsf{in}}_{\tau}, \langle t^{\mathsf{enc}}_{\tau}, \mathsf{Mac}^1_{\mathsf{k^{ID}_m}}(\langle t^{\mathsf{enc}}_{\tau}, g(\phi^{\mathsf{in}}_{\tau})\rangle)\rangle$$

$$\sigma^{\mathsf{up}}_{\tau} \equiv \begin{cases} \mathrm{SQN_U} \mapsto \mathsf{suc}(\sigma^{\mathsf{in}}_{\tau}(\mathrm{SQN^{ID}_U})) \\ \text{b-auth}_{\mathrm{U}} \mapsto g(\phi^{\mathsf{in}}_{\tau}) \end{cases}$$

$$\sigma_{\tau} \equiv \sigma^{\mathsf{in}}_{\tau} \cdot \sigma^{\mathsf{up}}_{\tau}$$

Base Axioms

Proposition: Mac Unforgeability

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

$$\overline{\mathsf{verify}_{\mathsf{k_m}}(s, m) \rightarrow \bigvee_{u \in \mathcal{S}} s = \mathsf{Mac}_{\mathsf{k_m}}(u)} \qquad (\text{EUF-MAC})$$

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Inference Rules

Function Application

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

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

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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Remarks

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

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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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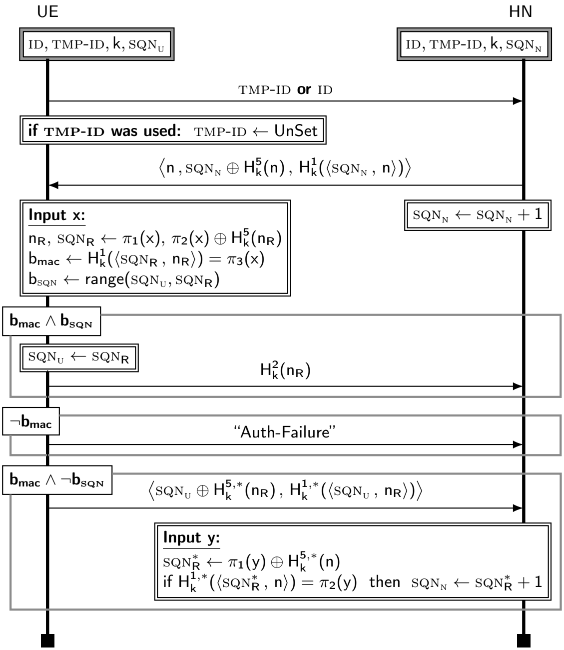
No Pre-Fetching of Authentication Vectors

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

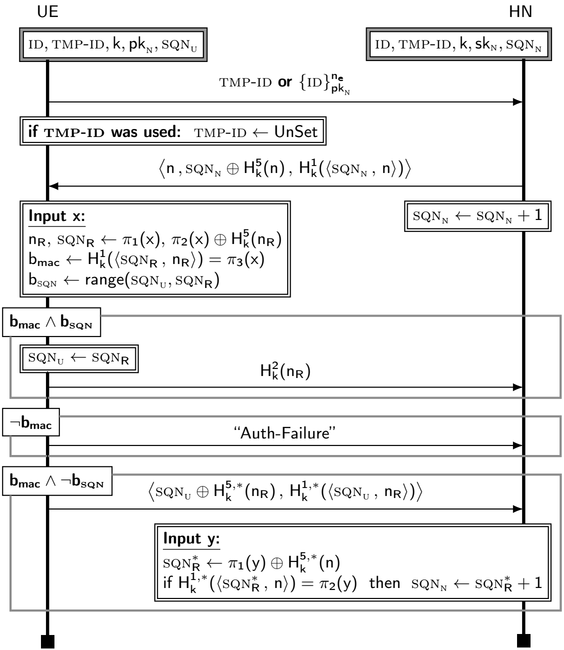
5G AKA does not support requesting multiple 5G AVs, neither the SEAF pre-fetching 5G AVs from the home network for future use.

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_k^5(n) , H_k^1(⟨SQN_N , n⟩)⟩
Input x:
n_R, SQN_R ← π_1(x), π_2(x) ⊕ H_k^5(n_R)
b_mac ← H_k^1(⟨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_k^2(n_R)
¬b_mac
"Auth-Failure"
b_mac ∧ ¬b_SQN
⟨SQN_U ⊕ H_k^{5,*}(n_R) , H_k^{1,*}(⟨SQN_U , n_R⟩)⟩
Input y:
SQN_R^* ← π_1(y) ⊕ H_k^{5,*}(n)
if H_k^{1,*}(⟨SQN_R^* , n⟩) = π_2(y) then SQN_N ← SQN_R^* + 1

5G-AKA


UE
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ID, TMP-ID, k, pk_N, SQN_U
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SQN_U ← SQN_R
H^2_k(n_R)
¬b_mac
"Auth-Failure"
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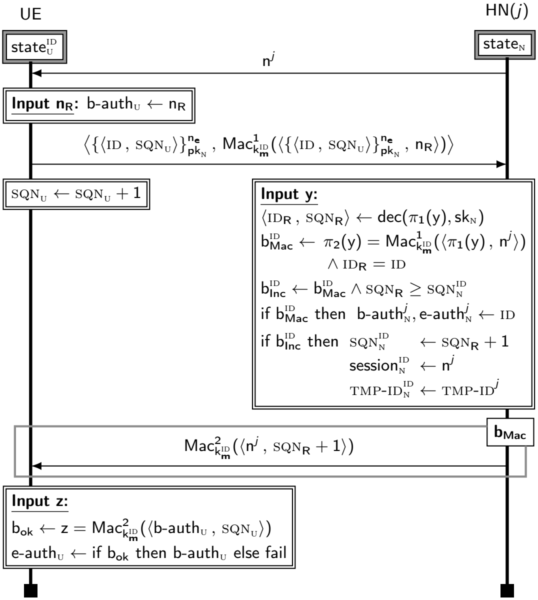
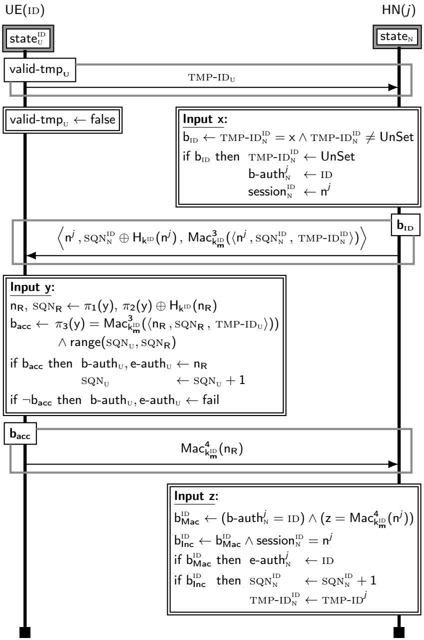
⟨SQN_U ⊕ H^{5,*}_k(n_R) , H^{1,*}_k(⟨SQN_U , n_R⟩)⟩
Input y:
SQN^*_R ← π_1(y) ⊕ H^{5,*}_k(n)
if H^{1,*}_k(⟨SQN^*_R , n⟩) = π_2(y) then SQN_N ← SQN^*_R + 1

ID Sub-Protocol



TMP-ID Sub-Protocol



The ASSIGN-TMP-ID Sub-Protocol

UE $\quad$ $\mathsf{state}_{\mathrm{U}}^{\mathrm{ID}}$

HN(j) $\quad$ $\mathsf{state}_{\mathrm{N}}$

$\mathsf{e\text{-}auth}_{\mathrm{N}}^{\mathrm{ID}} = \mathbf{ID}$

HN → UE: $\langle \textsc{tmp-id}^j \oplus \mathsf{H}^{\mathsf{r}}_{\mathsf{k}^{\mathrm{ID}}}(\mathsf{n}^j)\, ,\ \mathsf{Mac}^{5}_{\mathsf{k}^{\mathrm{ID}}_{\mathbf{m}}}(\langle \textsc{tmp-id}^j\, ,\ \mathsf{n}^j \rangle)\rangle$

Input x:

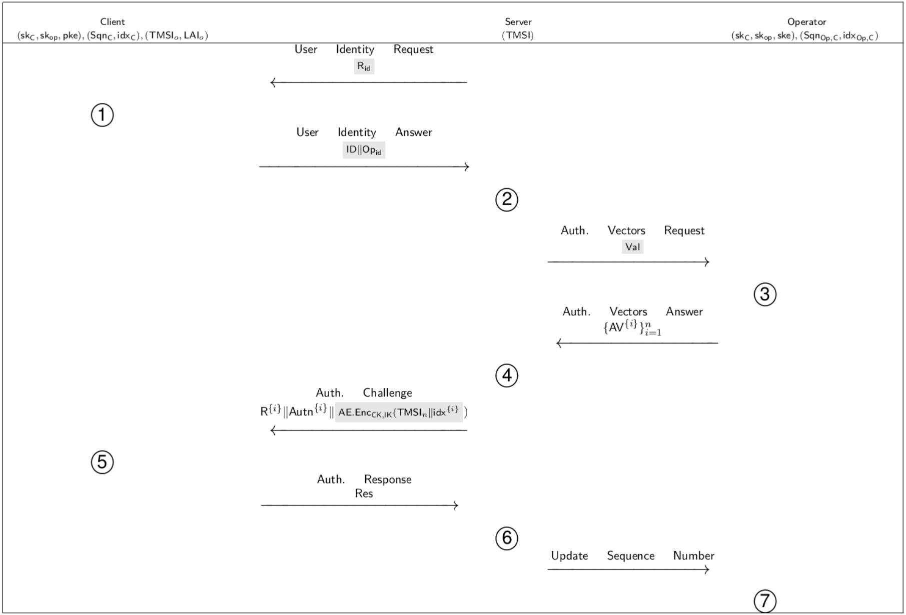
$\textsc{tmp-id}_{\mathsf{R}} \leftarrow \pi_1(\mathsf{x}) \oplus \mathsf{H}^{\mathsf{r}}_{\mathsf{k}^{\mathrm{ID}}_{\mathbf{m}}}(\mathsf{e\text{-}auth}_{\mathrm{U}})$

$\mathsf{b}_{\mathsf{acc}} \leftarrow \left(\pi_2(\mathsf{x}) = \mathsf{Mac}^{5}_{\mathsf{k}^{\mathrm{ID}}_{\mathbf{m}}}(\langle \textsc{tmp-id}_{\mathsf{R}}\, ,\ \mathsf{e\text{-}auth}_{\mathrm{U}}\rangle)\right)$
$\qquad \wedge (\mathsf{e\text{-}auth}_{\mathrm{U}} \neq \mathsf{fail})$

$\textsc{tmp-id}_{\mathrm{U}} \leftarrow$ if $\mathsf{b}_{\mathsf{acc}}$ then $\textsc{tmp-id}_{\mathsf{R}}$ else UnSet

$\mathsf{valid\text{-}tmp}_{\mathrm{U}} \leftarrow \mathsf{b}_{\mathsf{acc}}$

PRIV-AKA [Fouque et al., 2016]



PRIV-AKA [Fouque et al., 2016]

Client	Server	Operator
①: Compute the identifier: If $\mathsf{flag}_{\mathsf{TMSI}} := 0$ then ID = TMSI. Else, $\mathsf{ID} = \mathsf{PKE.Enc}_{\mathsf{pke}}(f_5(\mathsf{keys}, \mathsf{R}_{\mathsf{id}}, \mathsf{IMSI}, \mathsf{idx}_C) \| \mathsf{R}_{\mathsf{id}} \| \mathsf{IMSI} \| \mathsf{idx}_C)$. $\mathsf{flag}_{\mathsf{TMSI}} := 1$. ——— ⑤: Compute AK using $\mathsf{R}^{\{i\}}$. Recover $\mathsf{Sqn}^{\{i\}}$ (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 $\mathsf{flag}_{\mathsf{TMSI}} := 1$ and increment: $\mathsf{idx}_C := \mathsf{idx}_C + 1$. Else, check validity of $\mathsf{Sqn}^{\{i\}}$, i.e if one of the following conditions is correct: – $\mathsf{Sqn}_C = \mathsf{Sqn}^{\{i\}}$. – $\mathsf{Sqn}_C = \mathsf{inc}(\mathsf{Sqn}^{\{i\}})$ and $\mathsf{idx}^{\{i\}} = \mathsf{idx}_C + 1$. If the first condition is accepted: reset the index idx_C, update the sequence number $\mathsf{Sqn}_C = \mathsf{inc}(\mathsf{Sqn}_C)$. If the second condition is accepted: idx_C=idx_C+1. Compute $\mathsf{Res} := \mathcal{F}_1^*(\mathsf{keys}, \mathsf{R}^{\{i\}}, \mathsf{Sqn}^{\{i\}}, \mathsf{Res}_S, \mathsf{AMF})$. Update the internal index. Allocate the new TMSI. $\mathsf{flag}_{\mathsf{TMSI}} := 0$.	②: Process the identifier ID: If the identifier is a TMSI then Val = IMSI. Otherwise, $\mathsf{Val} = (\mathsf{ID}, \mathsf{R}_{\mathsf{id}})$. ——— ④: Store $\{\mathsf{AV}^{\{i\}}\}_{i=1}^{n}$. Choose $\mathsf{AV}^{\{i\}}$ one by one in order. Then, it sends the authentication challenge and the new couple $(\mathsf{TMSI}_n, \mathsf{idx}^{\{i\}})$ encrypted and authenticated by the session keys. ——— ⑥: If the authentication of the client is verified ($\mathsf{Res} \stackrel{?}{=} \mathsf{Mac}_C$), then they ask to the server the update of its sequence number. Otherwise, the protocol is aborted.	③: Verify the identity of the client with Val. If this holds, retrieve idx_C, set $\mathsf{idx}_{\mathsf{Op},C} := \mathsf{idx}_C$ Generate $(\mathsf{R}^{\{1\}}, \ldots, \mathsf{R}^{\{n\}})$. Denote: $\mathsf{keys} := (\mathsf{sk}_C, \mathsf{sk}_{\mathsf{op}})$. For each $i = 1, \ldots, n$, compute: $\mathsf{Mac}_S \leftarrow \mathcal{F}_1(\mathsf{keys}, \mathsf{R}^{\{i\}}, \mathsf{Sqn}^{\{i\}}, \mathsf{Res}_S, \mathsf{AMF})$, $\mathsf{Mac}_C \leftarrow \mathcal{F}_1^*(\mathsf{keys}, \mathsf{R}^{\{i\}}, \mathsf{Sqn}^{\{i\}}, \mathsf{Res}_S, \mathsf{AMF})$, $\mathsf{CK} \leftarrow \mathcal{F}_3(\mathsf{keys}, \mathsf{R}^{\{i\}}, \mathsf{Sqn}^{\{i\}}, \mathsf{Res}_S, \mathsf{AMF})$, $\mathsf{IK} \leftarrow \mathcal{F}_4(\mathsf{keys}, \mathsf{R}^{\{i\}}, \mathsf{Sqn}^{\{i\}}, \mathsf{Res}_S, \mathsf{AMF})$, $\mathsf{AK} \leftarrow \mathcal{F}_5(\mathsf{keys}, \mathsf{R}^{\{i\}}, \mathsf{Res}_S)$, $\mathsf{Autn}^{\{i\}} \leftarrow (\mathsf{Sqn}^{\{i\}} \oplus \mathsf{AK}) \| \mathsf{AMF} \| \mathsf{Mac}_S$, $\mathsf{Sqn}^{\{i\}} \leftarrow \mathsf{inc}(\mathsf{Sqn}^{\{i-1\}})$, $\mathsf{AV}^{\{i\}} := (\mathsf{R}^{\{i\}}, \mathsf{CK}, \mathsf{IK}, \mathsf{Autn}^{\{i\}}, \mathsf{Mac}_C, \mathsf{idx}^{\{i\}})$, with $\mathsf{Sqn}^{\{1\}} := \mathsf{Sqn}_{\mathsf{Op},C}$, $\mathsf{idx}^{\{1\}} := \mathsf{idx}_{\mathsf{Op},C}$, $\forall i \neq 1, \mathsf{idx}^{\{i\}} = 0$. End for. ——— ⑦: Update the sequence number: $\mathsf{Sqn}_{\mathsf{Op},C} \leftarrow \mathsf{inc}(\mathsf{Sqn}_{\mathsf{Op},C})$. Reset the index $\mathsf{idx}_{\mathsf{Op},C}$.

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