Privacy-Preserving Authenticated Key Exchange in the Standard Model

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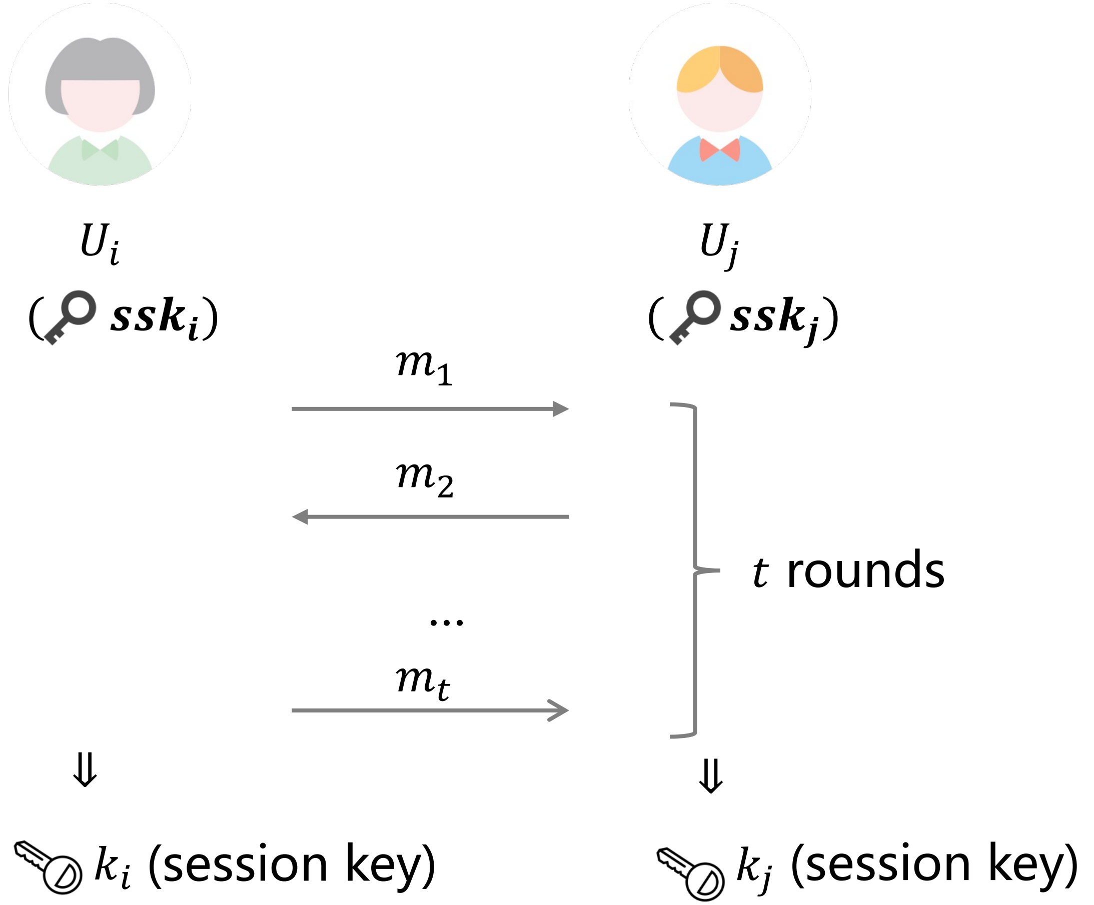
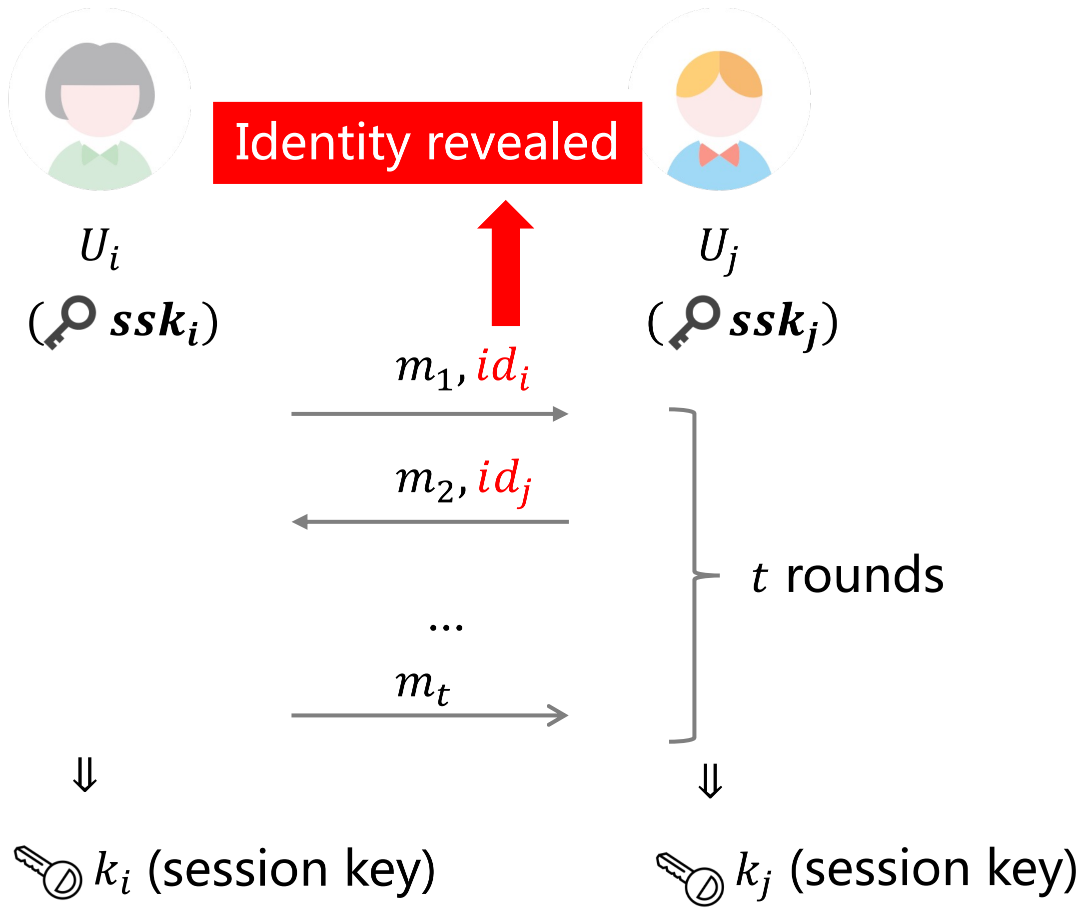
Authenticated Key Exchange (AKE)



- AKE allows two parties to authenticate each other and securely share a session key.
- It has been widely used in data sharing, electronic notebooks, etc.

Privacy-Preserving AKE (PPAKE)



- AKE allows two parties to authenticate each other and securely share a session key.
- It has been widely used in data sharing, electronic notebooks, etc.
- AKE protocol provides no security on users' identities.
- To solve this problem, PPAKE was proposed.
- Privacy-Preserving: It requires anonymity, which means the adversary cannot identify the users who are communicating.

Most AKE protocols are not Privacy-Preserving

Signed-DH AKE

U_i $\boldsymbol{vk_i}$

$(\boldsymbol{sk_i})$

U_j $\boldsymbol{vk_j}$

$(\boldsymbol{sk_j})$

$$g^a, Sign(sk_i, i|j|g^a) \longrightarrow$$

$$\longleftarrow g^b, Sign(sk_j, i|j|g^a|g^b)$$

$\Downarrow$

$k_i = g^{ab}$

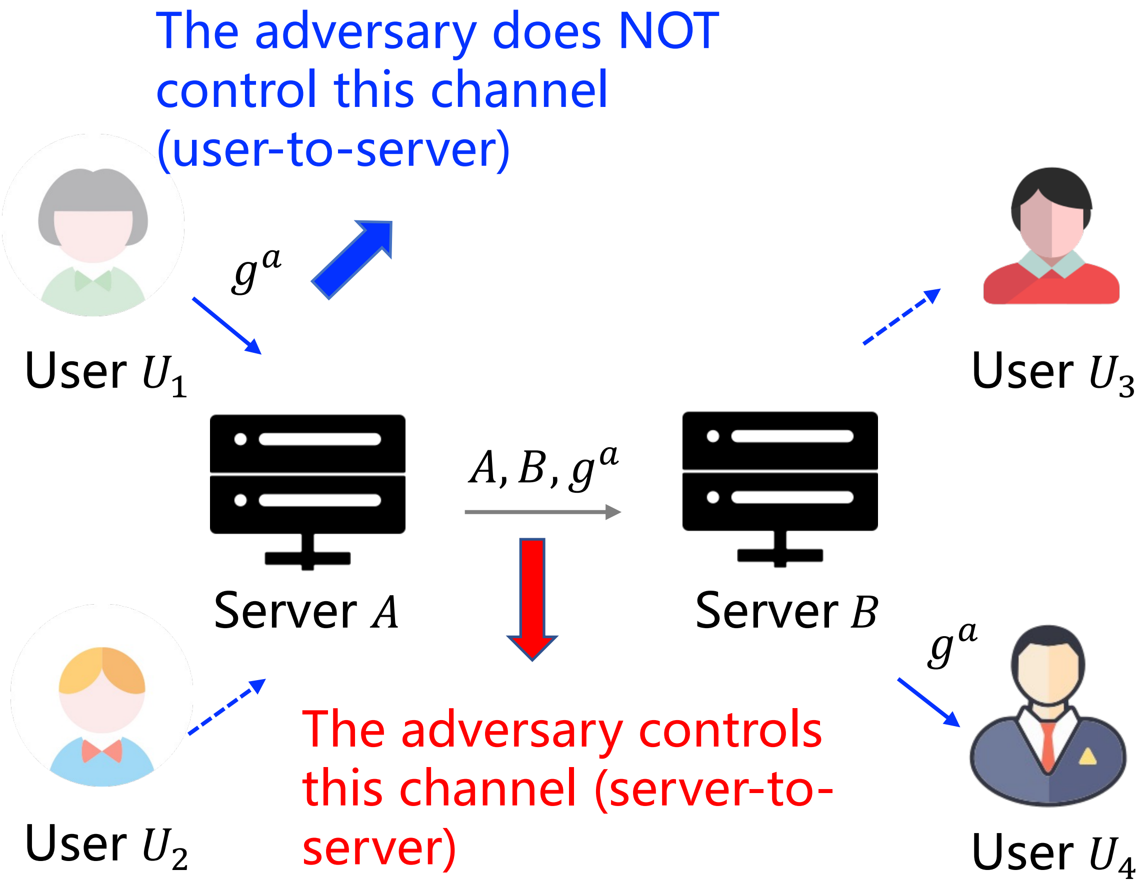
$\Downarrow$

$k_j = g^{ab}$

- Most AKE protocols are not privacy-preserving.
- For example, the well-know Signed-DH AKE is not PPAKE
- Anonymity: No other user can identify which two people are communicating

The signature leaks the identity of both initiator and responder.

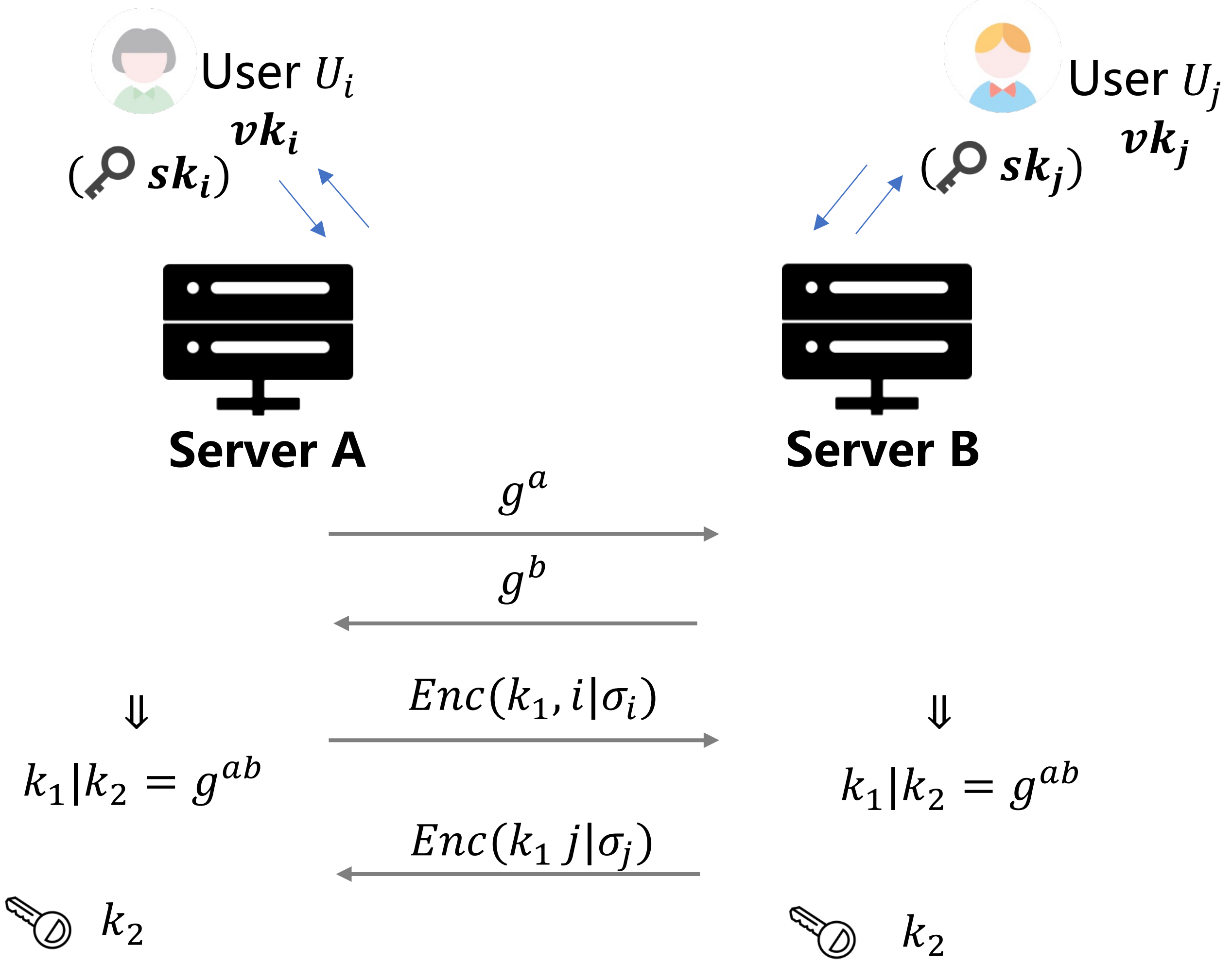
Previous work on PPAKE: SSL-PPAKE



- [SSL20] proposed a way to protect the identity of users with PPAKE.
- It considers the Server-to-Server scenario.
- Many users sit behind some servers. But The adversary does NOT control channel of user-to-server
- Anonymity requires the adversary cannot distinguish which user sits behind the server.

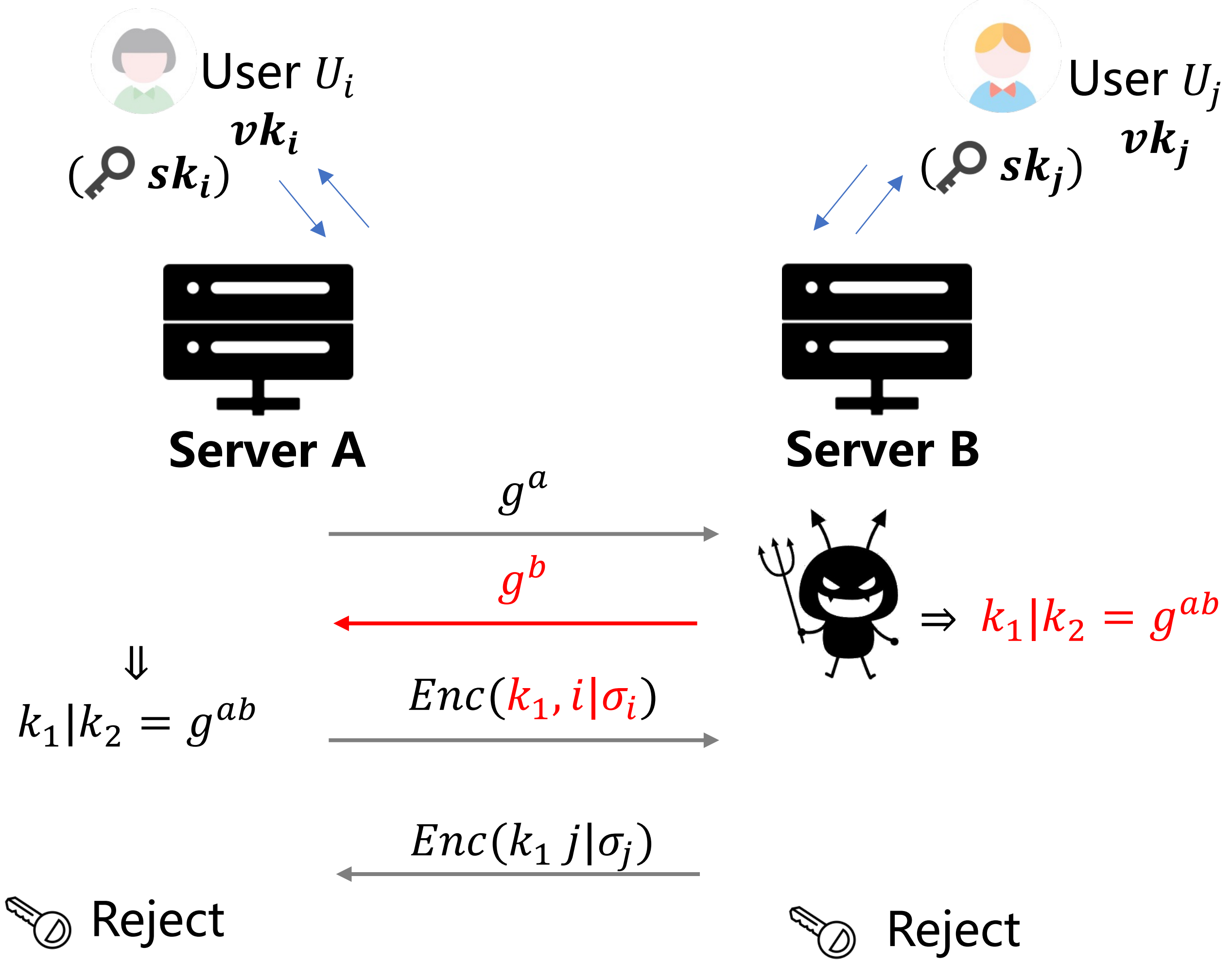
Privacy-Preserving Authenticated Key Exchange and the Case of IKEv2.
Sven Schäge, Jörg Schwenk, Sebastian Lauer PKC 2020

Previous work: SSL-PPAKE



- Both users first do an anonymous DH key exchange to get an ephemeral key.
- Then they use the ephemeral key to encrypt the signature to hide their identity.

Previous work: SSL-PPAKE

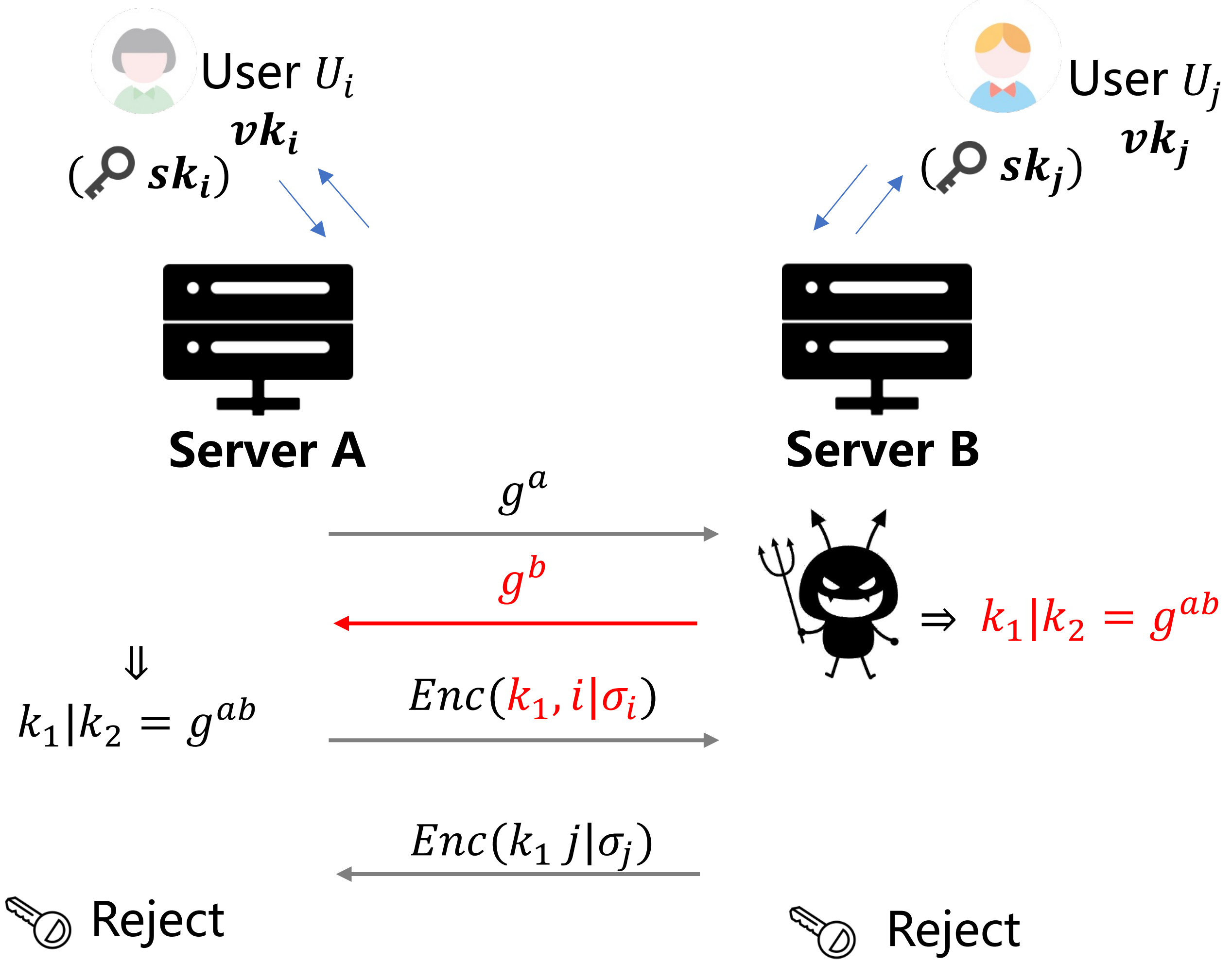


- Due to the lack of authenticity in the first two rounds, it suffers an active attack.

  An adversary can send the second message to get the identity of the initiator.

- It considers the server-to-server scenario (e.g. network protocol)
- It does not apply to the user-to-user scenario (e.g. WLAN, Bluetooth, Apple Airdrop)， which we will discuss later.

Previous work: SSL-PPAKE



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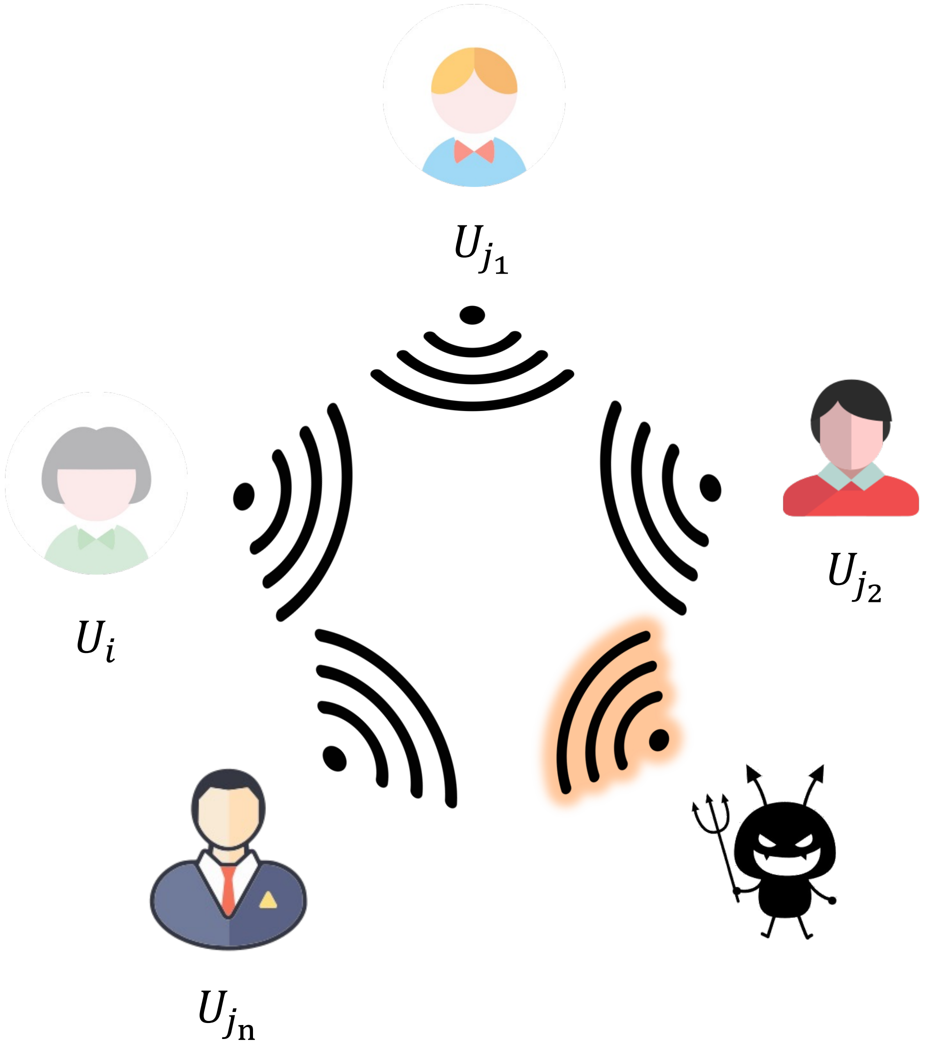
- It considers the server-to-server scenario (e.g. network protocol)
- It does not apply to the user-to-user scenario (e.g. WLAN, Bluetooth, Apple Airdrop).

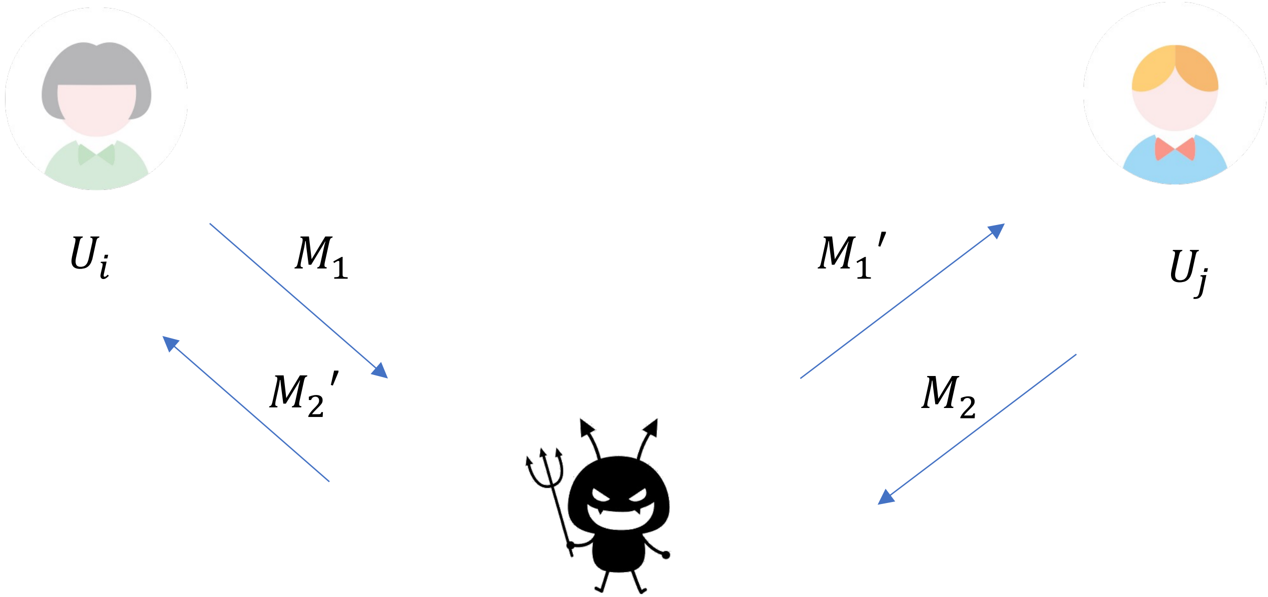
Question: How to design a PPAKE protocol for the user-to-user scenario?

The user-to-user scenario



- In the user-to-user scenario, there are no agent servers.
- We consider the broadcast channel (just like the scenario of Bluetooth, WLAN, and Airdrop).
- The adversary can see the message in the broadcast channel and involve in the communication of users.

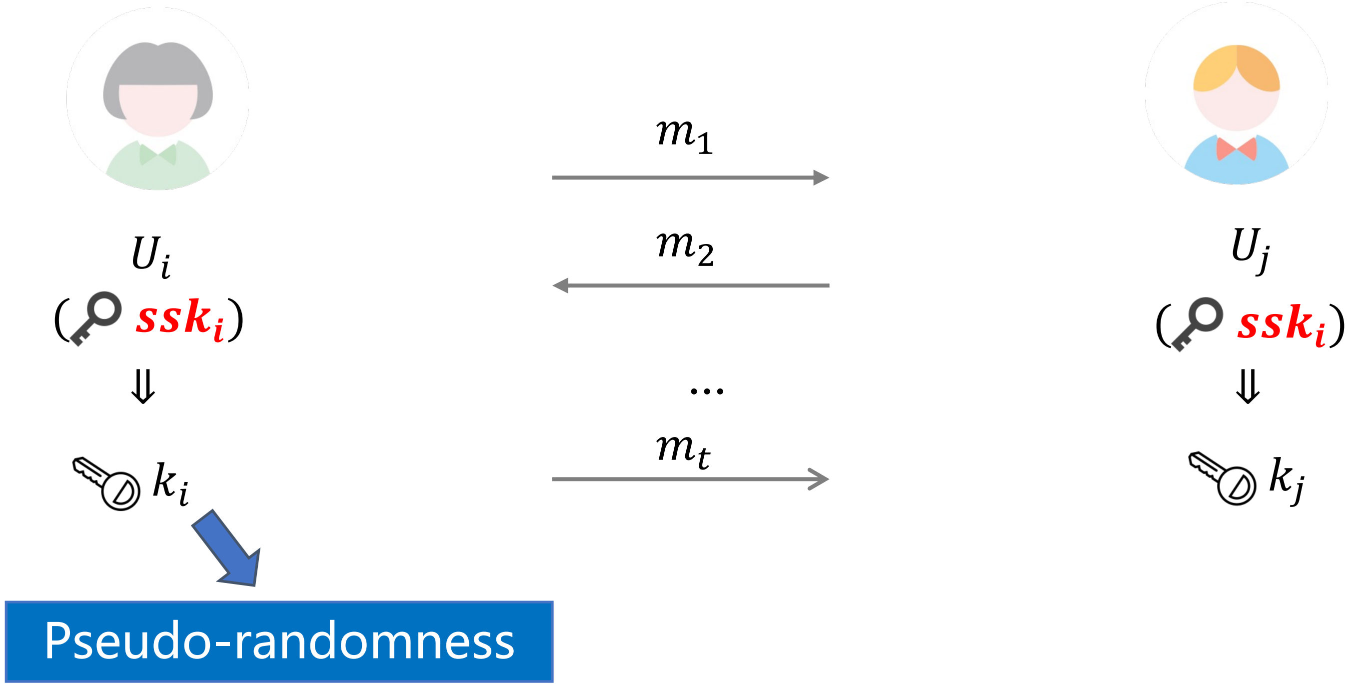
(Explicit) Authentication of PPAKE



Explicit Authentication: Active attack can be identified. For each accepted user U_i, there is a unique partner U_j such that the output of U_j is the input of U_i, and The output of U_i is the input of U_j

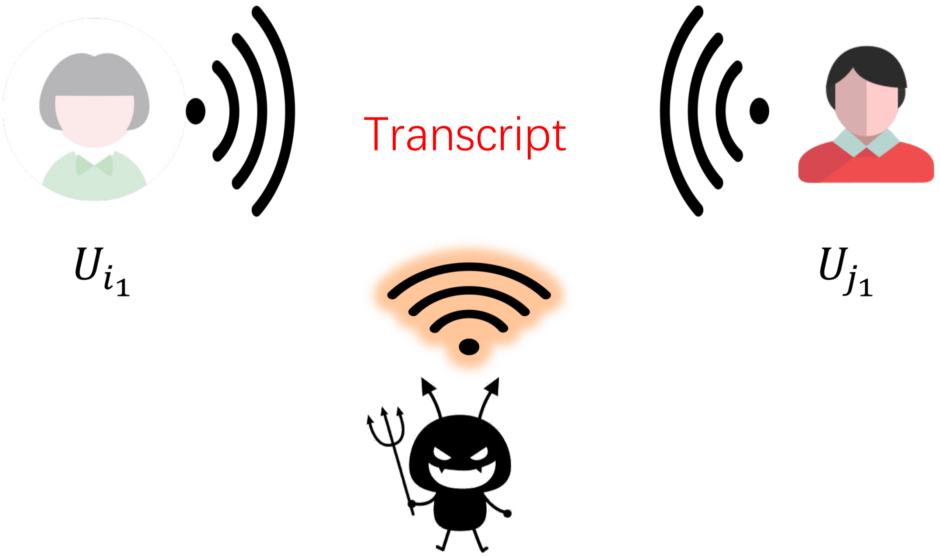
$$M_1 = M_1' \text{ and } M_2 = M_2'$$

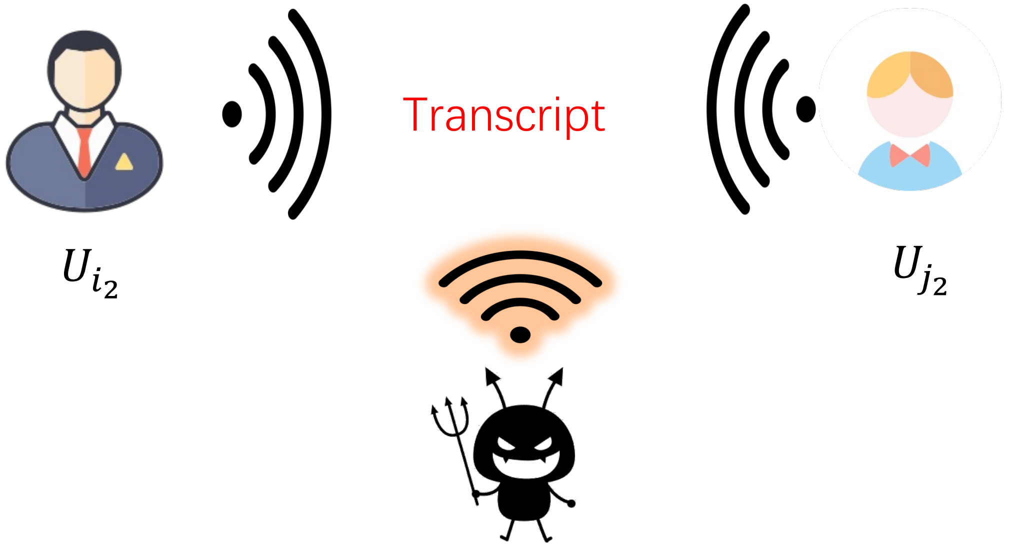
(Forward) Security for Session Key



Forward Security for Session Key: The session key is pseudo-random if there are no active attacks, even if the long-term key of users are leaked to the adversary.

Anonymity for User Identity

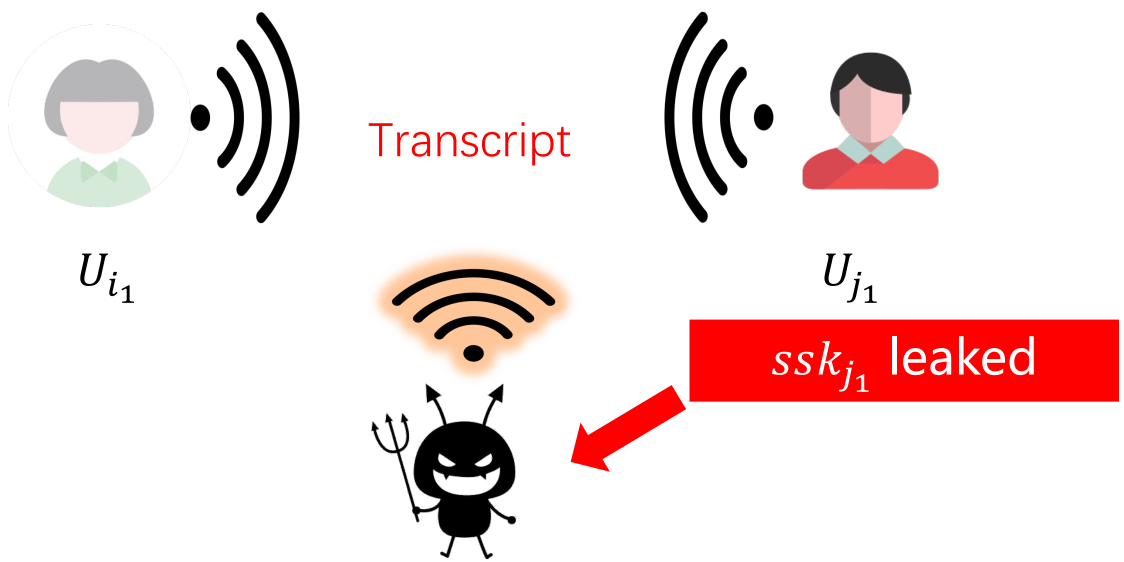




Anonymity: given the transcript, the adversary can not distinguish which two users are communicating

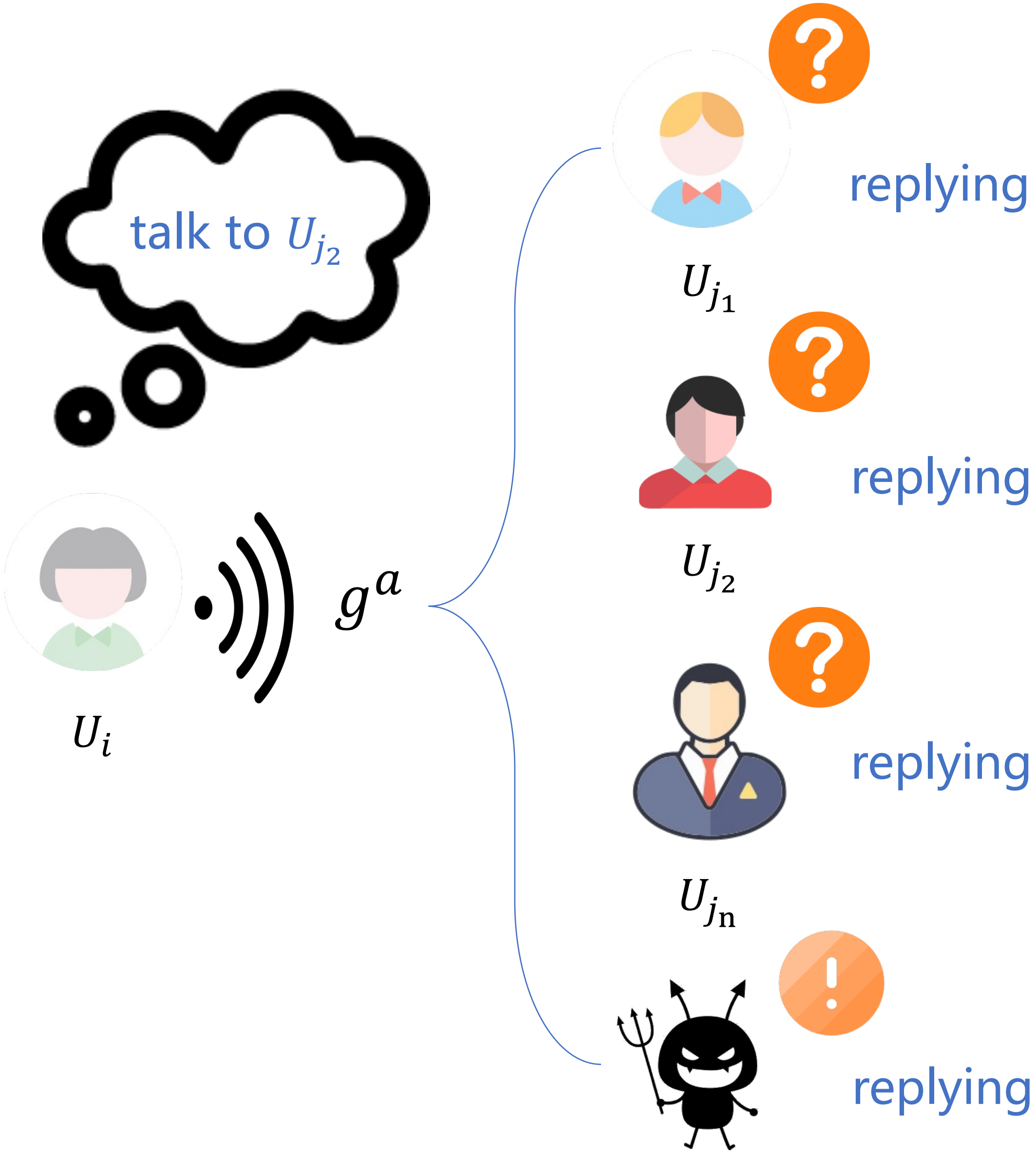
Forward Anonymity: anonymity holds even if the adversary can also corrupt these users (get their long-term keys) after it gets the transcript.

Forward Anonymity



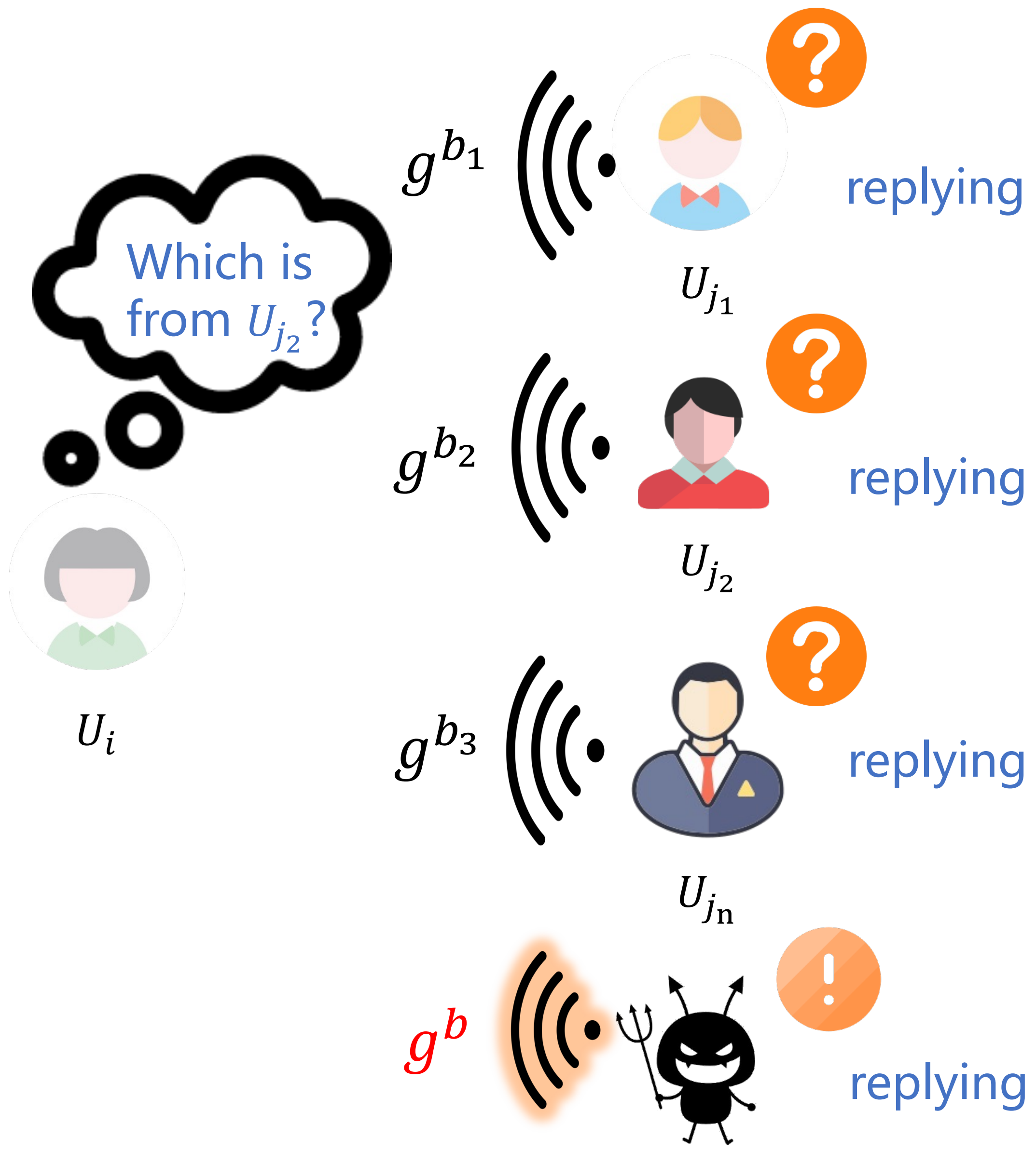
- Suppose the adversary gets the long-term key of user U_{j_2}
- Based on the previous transcript, adversary can not determine whether user U_{j_2} was involved in the previous communication.

SSL-PPAKE for user-to-user setting



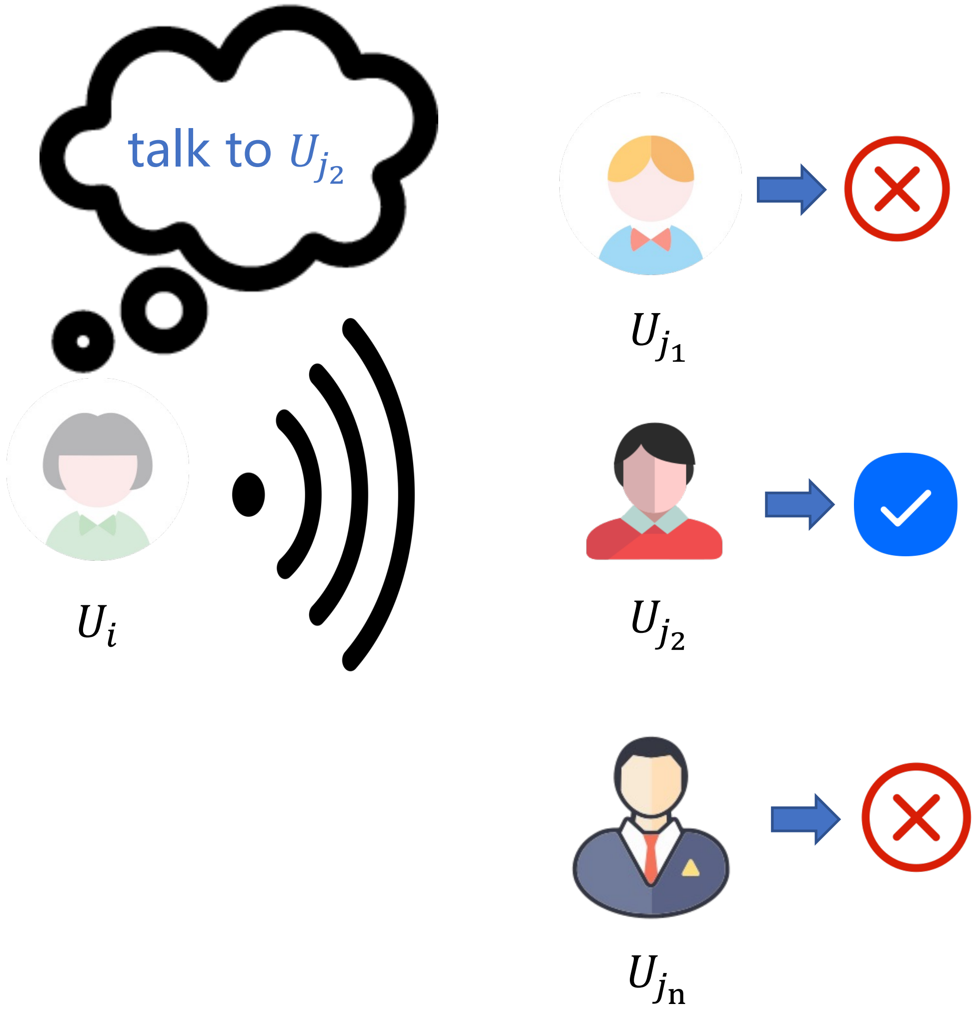
- To protect the identity of U_{j_2}, the first message does not contain any information of its target recipient.
- each user is not sure whether itself is the target recipient.
- Hence, each user must reply with a g^b

SSL-PPAKE for user-to-user setting



- To protect the identity of U_{j_2}, the first message does not contain any information of its target recipient.
- each user is not sure whether itself is the target recipient.
- Hence, each user must reply with a g^b
- This will cause large communication and computation complexity.
- Moreover, the adversary can always determine the initiator's identity.

Our Approach: Making PPAKE Robust



- Robust PPAKE: any user except the target recipient will output $\perp$ when they receive the first round message of PPAKE.
- In other words, each user is able to ascertain that the message in the first round is for him/her.
- Due to the robustness, the communication and computation complexity can be reduced.

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Building Blocks of Our Construction

We propose a generic construction of PPAKE from the following building blocks:

- Signature Scheme (Sign, Verify)
- Key Encapsulation Mechanism (Encap, Decap)
- Message Authentication Code (MAC, Verify)
- Symmetric Encryption (Enc, Dec)

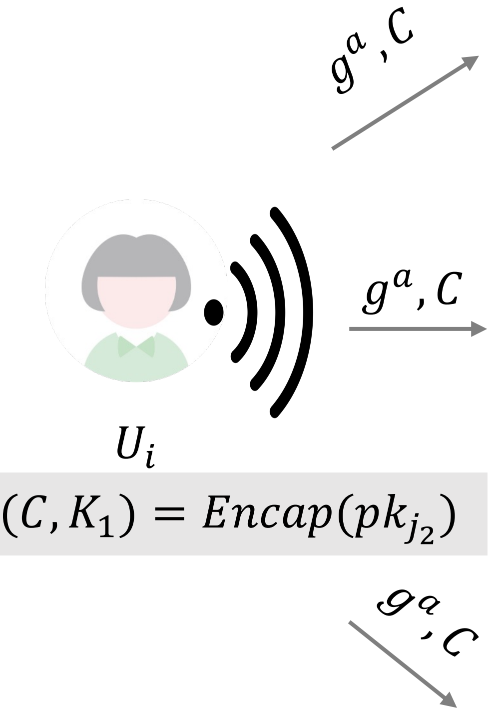
The Requirements for KEM

Key Encapsulation Mechanism (KEM):

- $\mathrm{KEM.Gen}(1^\lambda; r) \to (pk, sk)$
- $\mathrm{KEM.Encap}(pk; r) \to (C, K)$
- $\mathrm{KEM.Decap}(sk, C) \to K'$

- Anonymity: the adversary cannot distinguish whether the ciphertext C is generated by pk_0 or pk_1
- Robustness: If a ciphertext is generated by pk_b, then $\mathrm{Decap}(sk_{1-b}, C) = \perp$ with overwhelming probability.

Our Construction: The First Round



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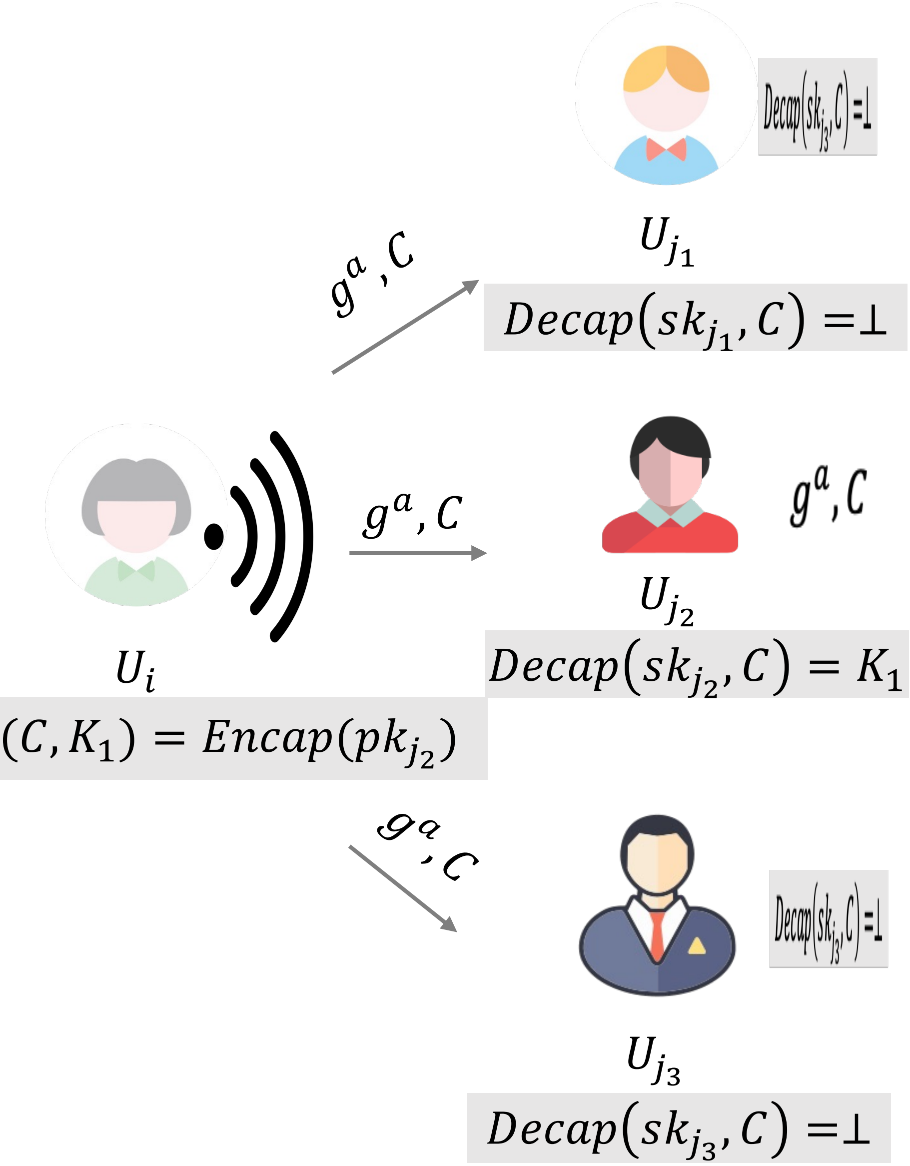
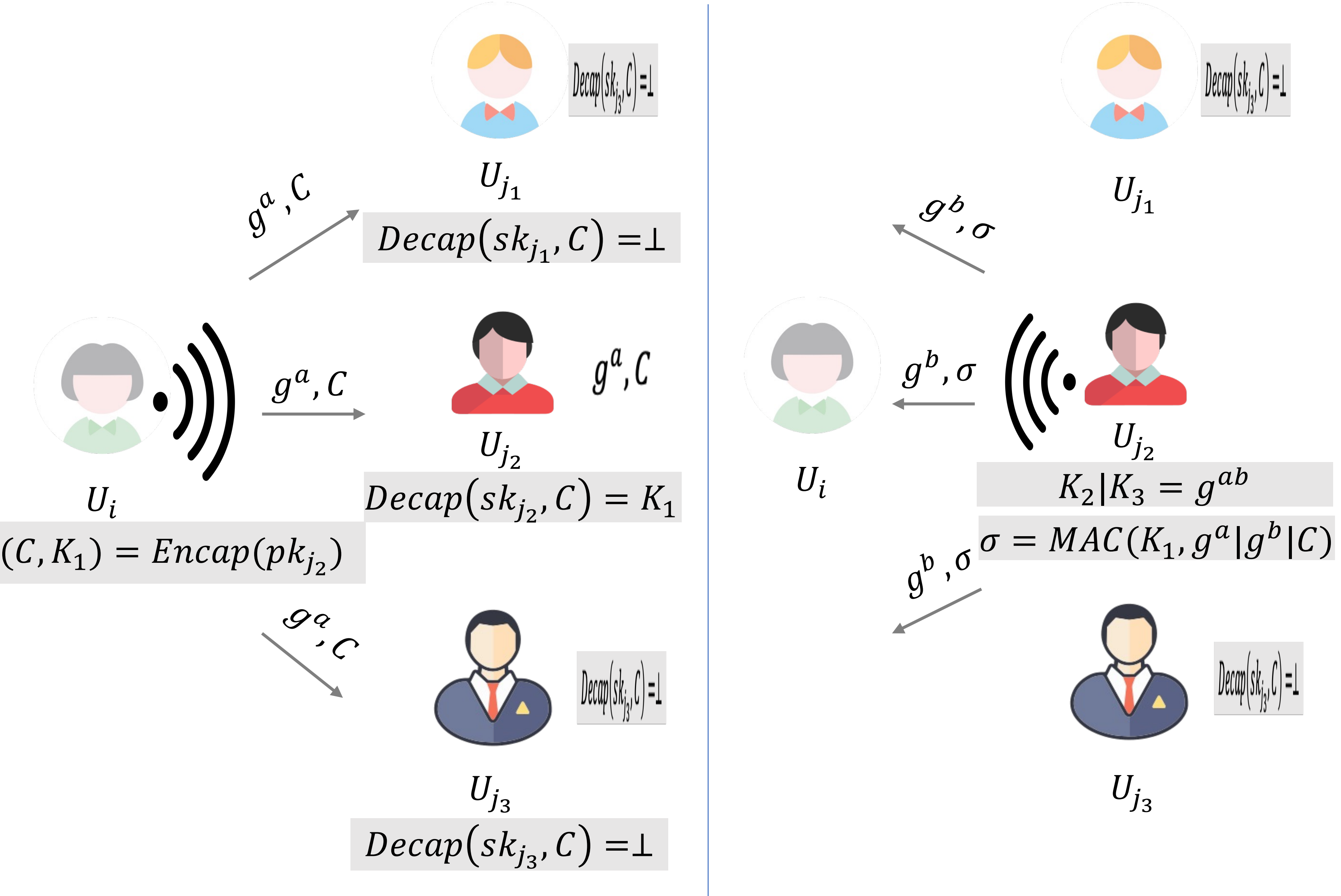
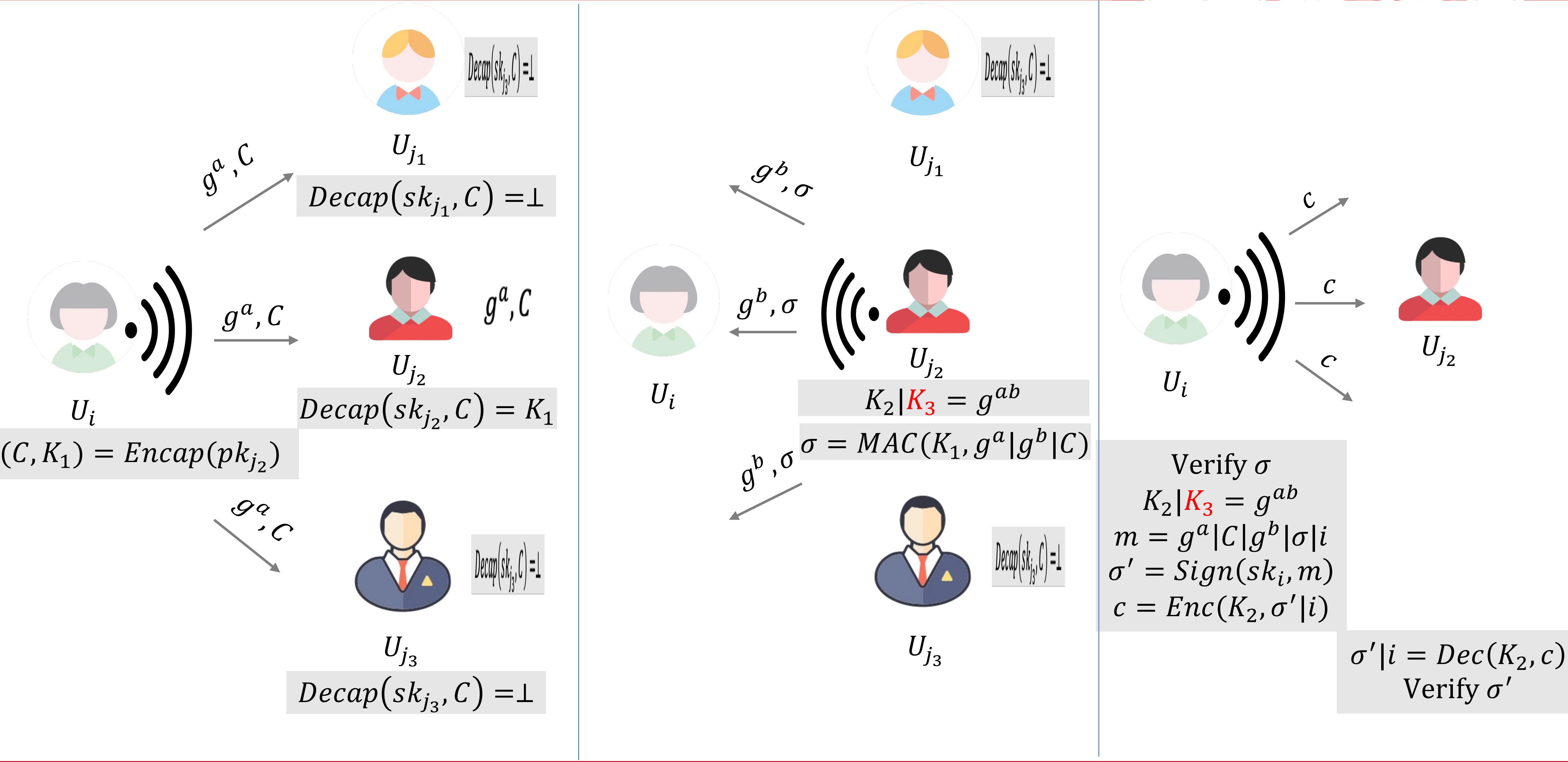


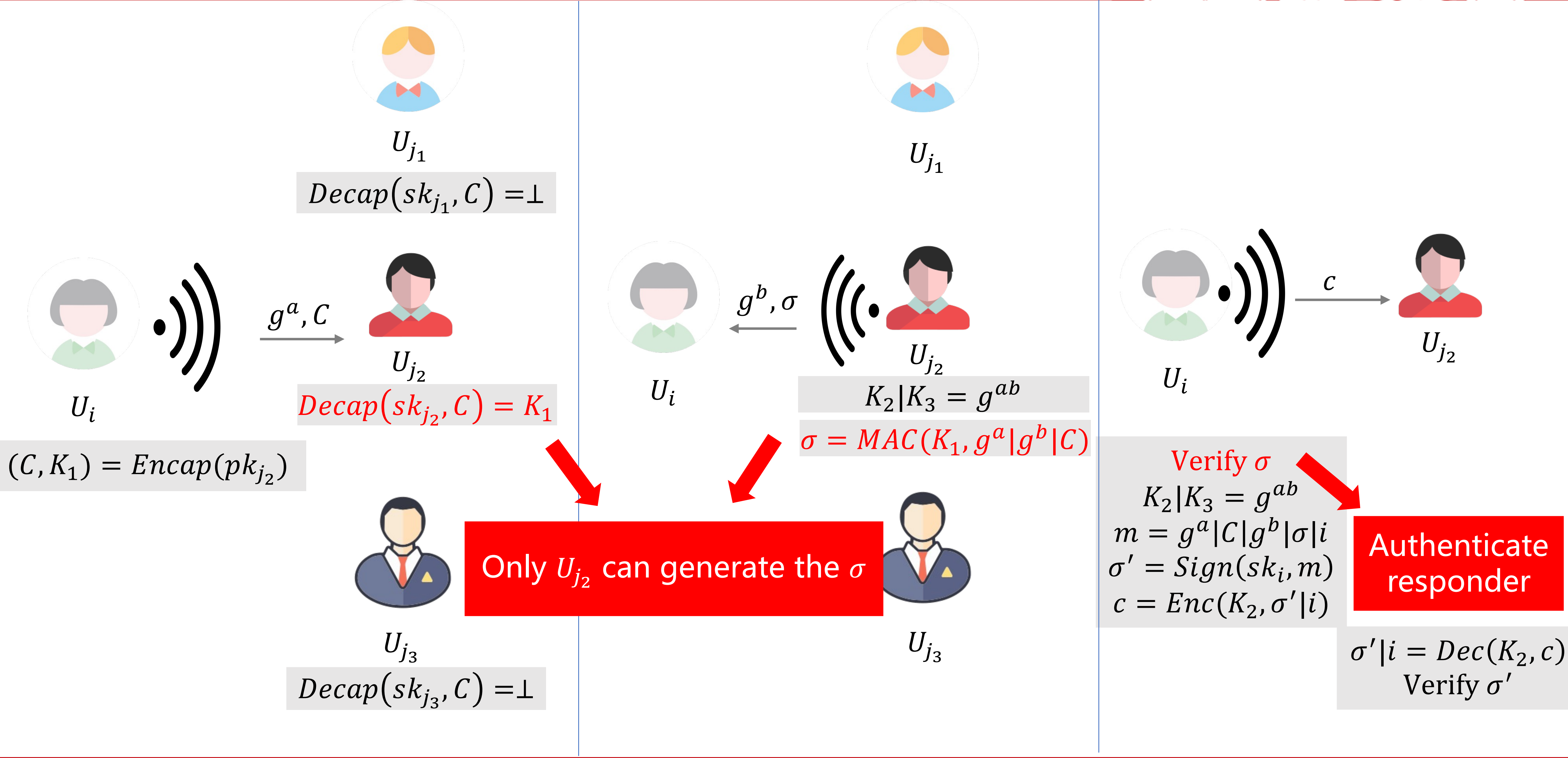
Our Construction: The Second Round



Our Construction: The Third Round



Authentication



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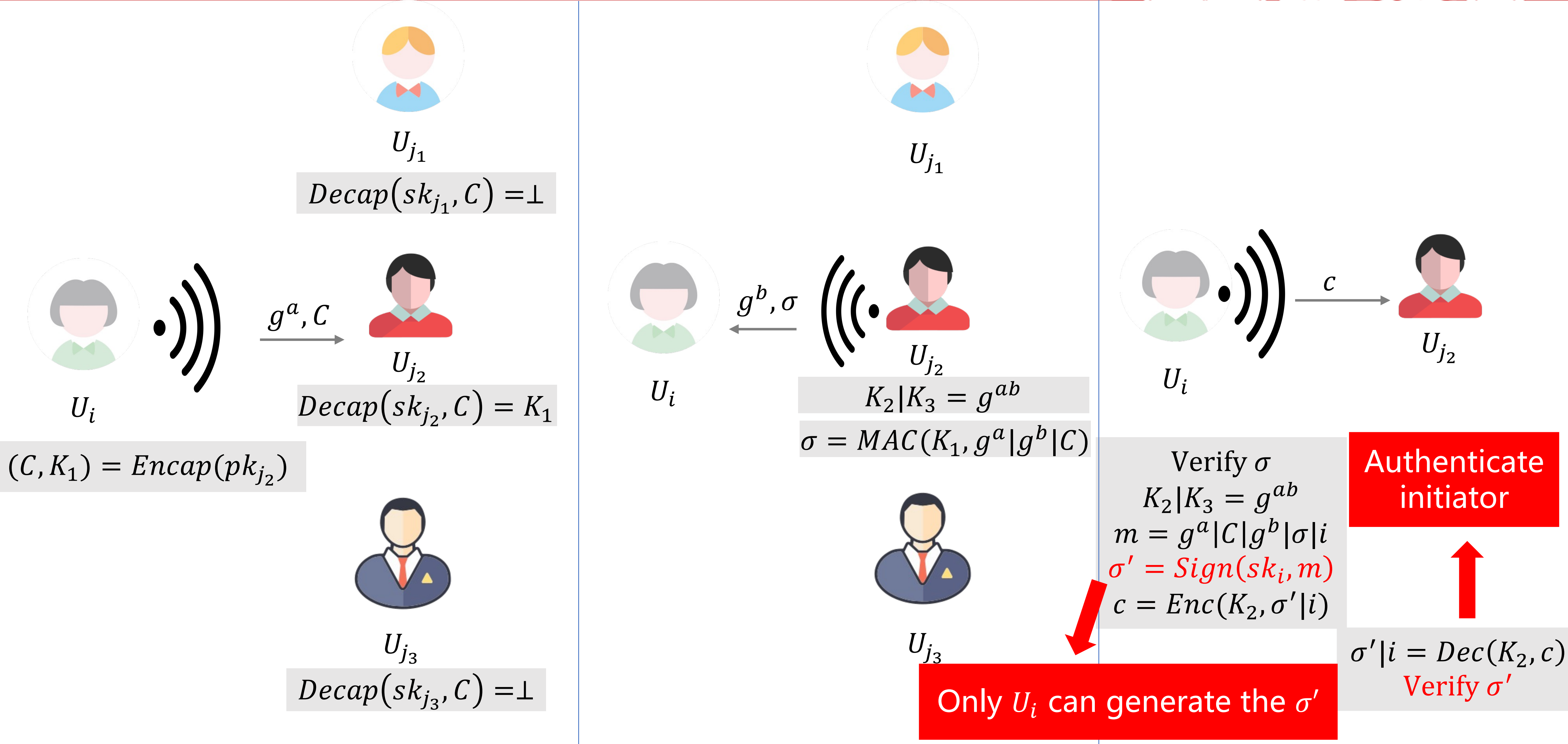
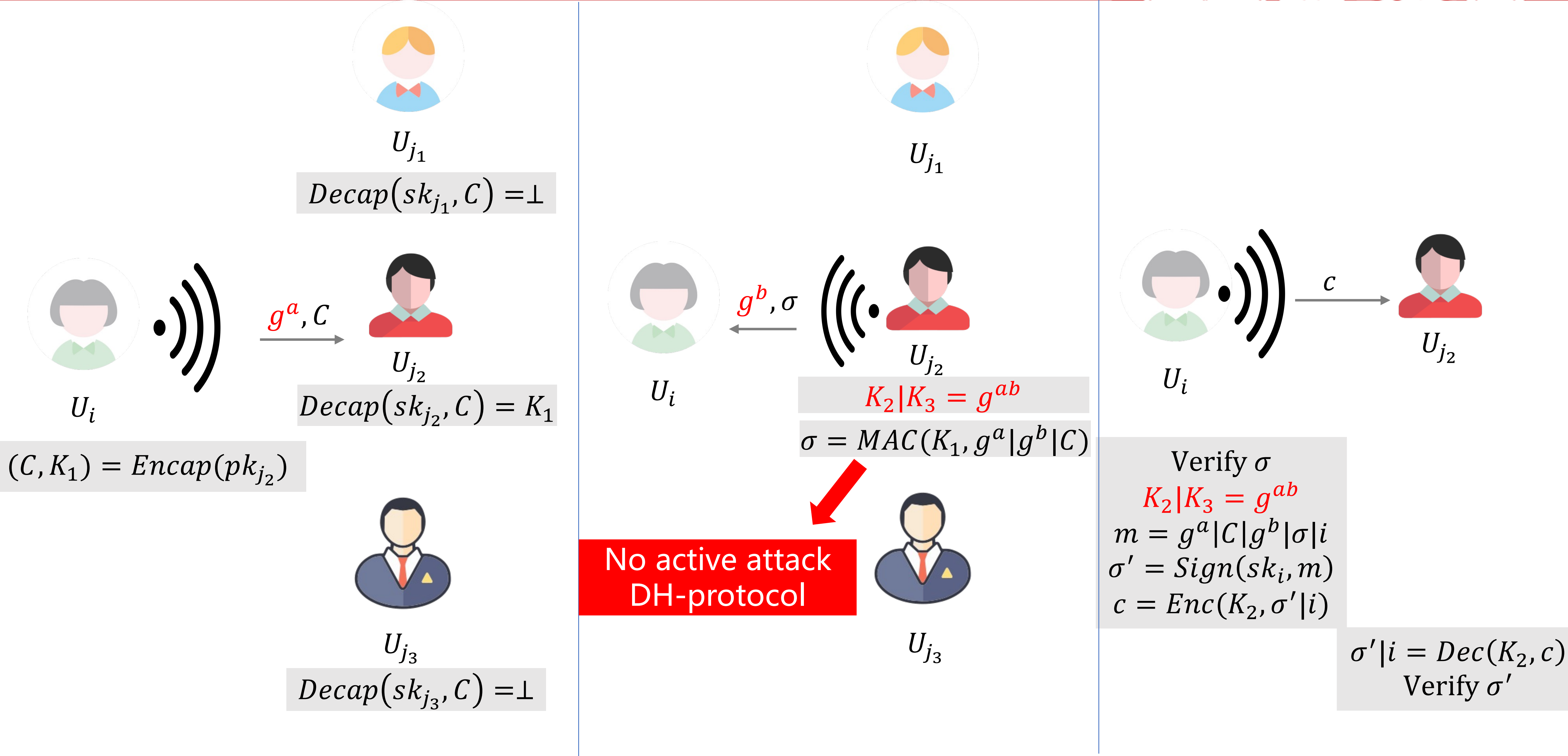


Forward security (Key Pseudo-Randomness)



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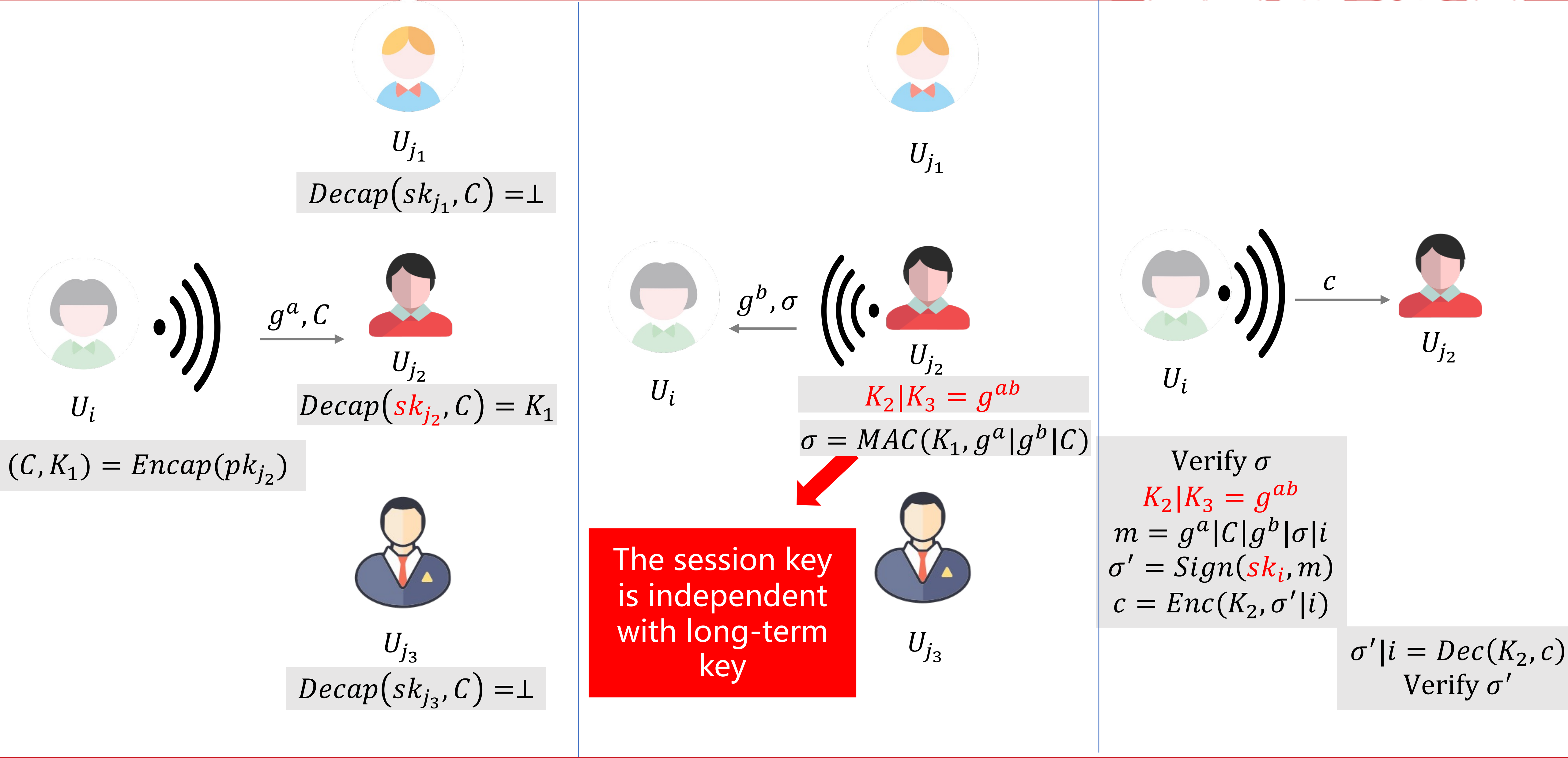
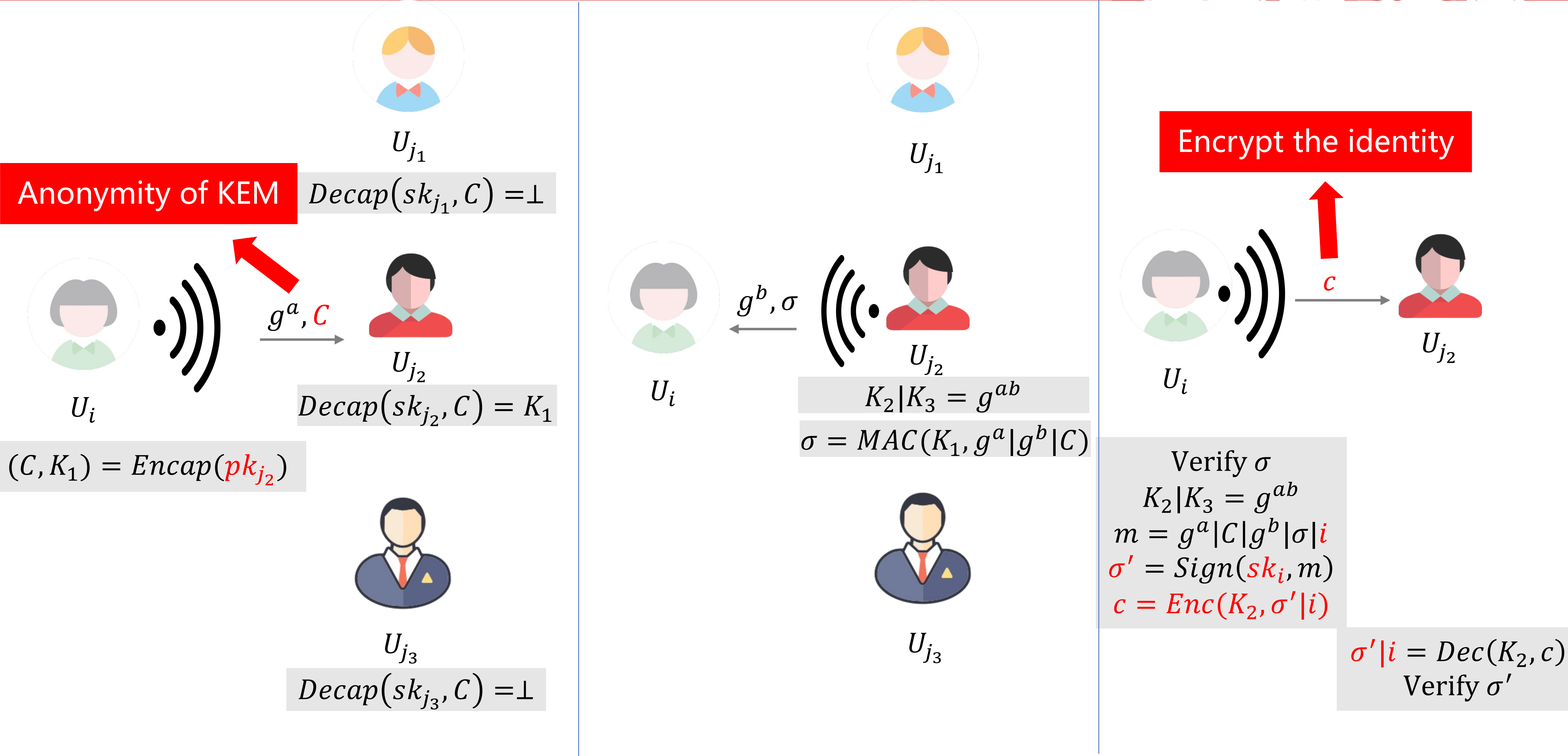
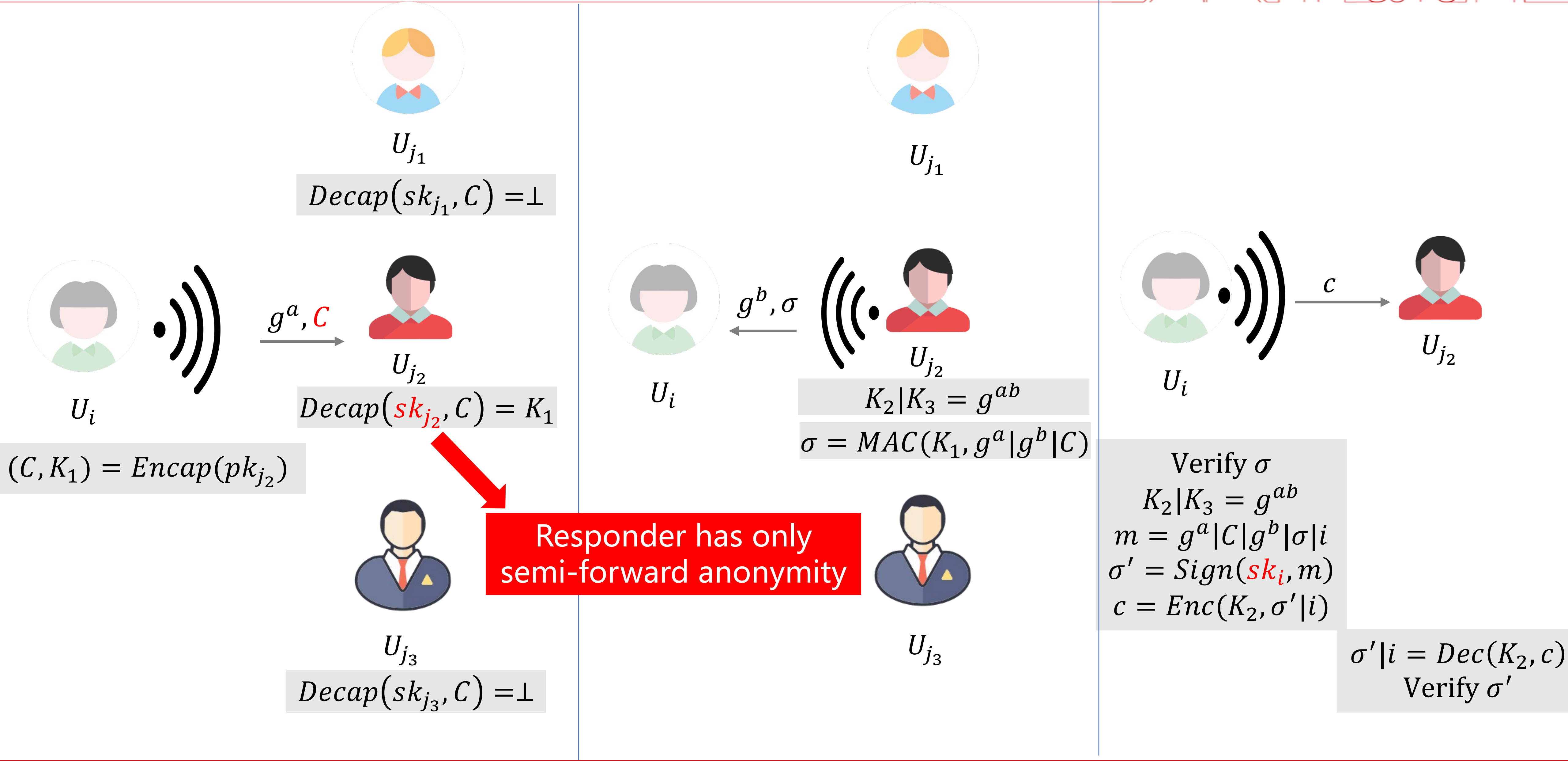


Anonymity



U_{j_1}
Anonymity of KEM
$Decap(sk_{j_1}, C) = \perp$
g^a, C
U_i
U_{j_2}
$Decap(sk_{j_2}, C) = K_1$
$(C, K_1) = Encap(pk_{j_2})$
U_{j_3}
$Decap(sk_{j_3}, C) = \perp$
U_{j_1}
g^b, σ
U_i
U_{j_2}
$K_2|K_3 = g^{ab}$
$\sigma = MAC(K_1, g^a|g^b|C)$
U_{j_3}
Encrypt the identity
c
U_i
U_{j_2}
Verify σ
$K_2|K_3 = g^{ab}$
$m = g^a|C|g^b|\sigma|i$
$\sigma' = Sign(sk_i, m)$
$c = Enc(K_2, \sigma'|i)$
$\sigma'|i = Dec(K_2, c)$
Verify σ'

Semi-forward Anonymity for Responder



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Comparison

PPAKE schemes	Comm	Comp	#	Forward Security	Anonymity		Forward Anonymity CrpI		Forward Anonymity CrpR		Mutual Auth	Std
					I	R	I	R	I	R		
IY22	6	$O(1)$	2	weak	✓	×	✓	×	✓	×	×	✓
SKEME96	16	$O(1)$	3	✓	✓	✓	×	×	×	×	✓	×
SSL20	5μ	$O(\mu)$	4	✓	×	✓	×	✓	×	✓	✓	✓
RSW21	$7\mu - 5$	$O(\mu)$	4	✓	✓	✓	✓	✓	×	×	✓	×
Ours	12	$O(1)$	3	✓	✓	✓	✓	✓	✓	×	✓	✓

Consider all protocols in the user-to-user setting.

μ: number of users in the system.

Thanks to robustness, the computation complexity and communication complexity are independent of μ.

Conclusion

- In this paper, we propose a PPAKE scheme, especially for the broadcast channel and user-to-user setting
- We also give a concrete instantiation based on DDH assumption.
- For more information, please refer to our paper.

  https://eprint.iacr.org/2022/1217.pdf

- An interesting problem:

  Can we construct a PPAKE scheme that satisfied full-forward anonymity in our model?

Thanks! Questions?

References

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[SSL20] Sven Schäge, Jörg Schwenk, Sebastian Lauer: Privacy-Preserving Authenticated Key Exchange and the Case of IKEv2. Public Key Cryptography (2) 2020: 567-596

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