A Concrete Treatment of Efficient Continuous Group Key Agreement via Multi-Recipient PKEs

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Outline

Efficient post-quantum CGKA protocol

1. Background
2. Our solution: Chained CmPKE
3. More efficient PQ multi-recipient PKEs
4. Comparison and implementation

Background: Secure (Group) Messaging

Secure (Group) Messaging

Recently, a lot of people use secure (group) messaging apps.

Applications	Num. of monthly active users
WhatsApp	2.0 billion
Facebook Messenger	1.3 billion
Telegram	550 million
Snapchat	514 million

Ref: https://www.statista.com/statistics/258749/most-popular-global-mobile-messenger-apps/

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Because governments and hackers try to gather personal information.

- "NSA Prism program taps into user data of Apple, Google and others", The Guardian, 2013
  https://www.theguardian.com/world/2013/jun/06/us-tech-giants-nsa-data
- "Al Jazeera journalists 'hacked via NSO Group spyware'", BBC, 2020
  https://www.bbc.com/news/technology-55396843
- "Grand jury subpoena for Signal user data, Central District of California", Signal , 2020
  https://signal.org/bigbrother/central-california-grand-jury/

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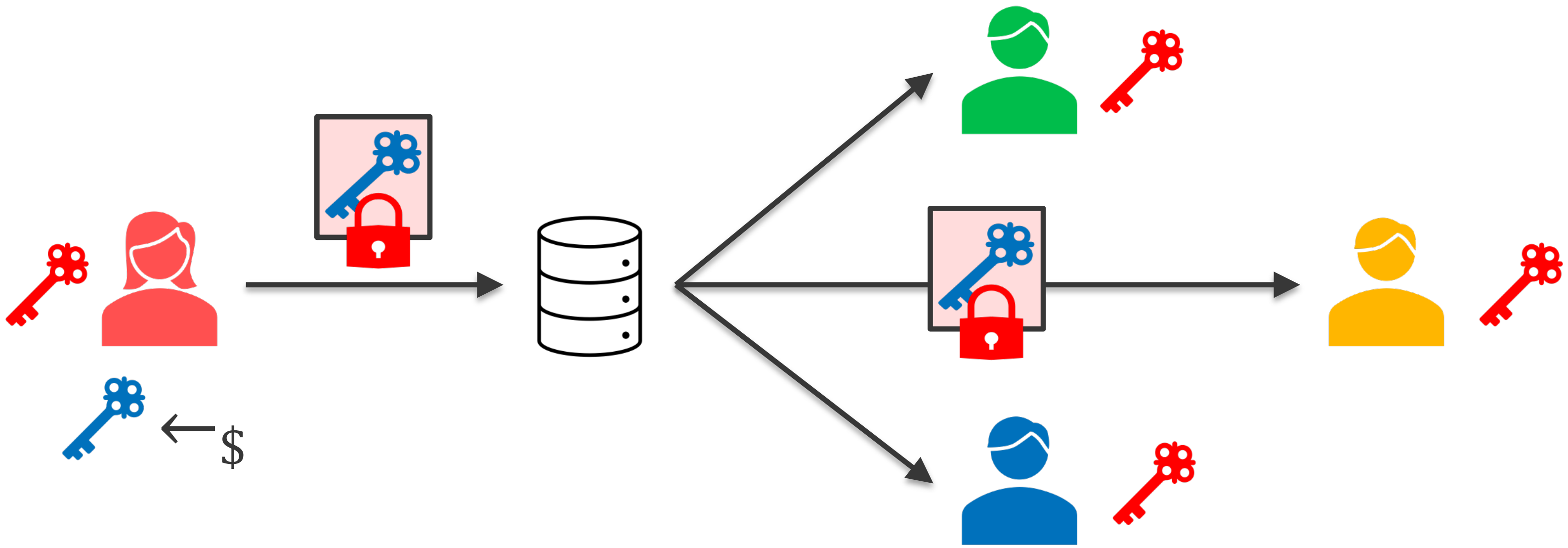
Existing secure (group) messaging:

- 2-party messaging: Signal protocol
  - Analyzed by a lot of works [CGC+17, ACD19, BFG+20, HKKP21]
- Group messaging : Continuous Group Key Agreement (this talk)

Continuous Group Key Agreement (CGKA) [ACDT20]

Group key agreement protocols that concentrate the cryptographic mechanisms of secure group messaging protocols:

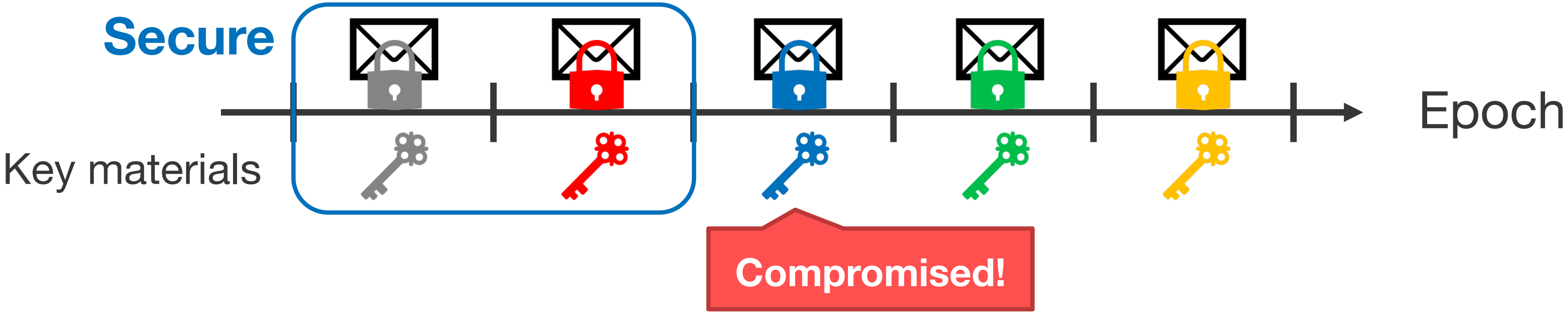
- Add a party to the group
- Remove a party from the group
- **Update key materials** (Ratcheting)



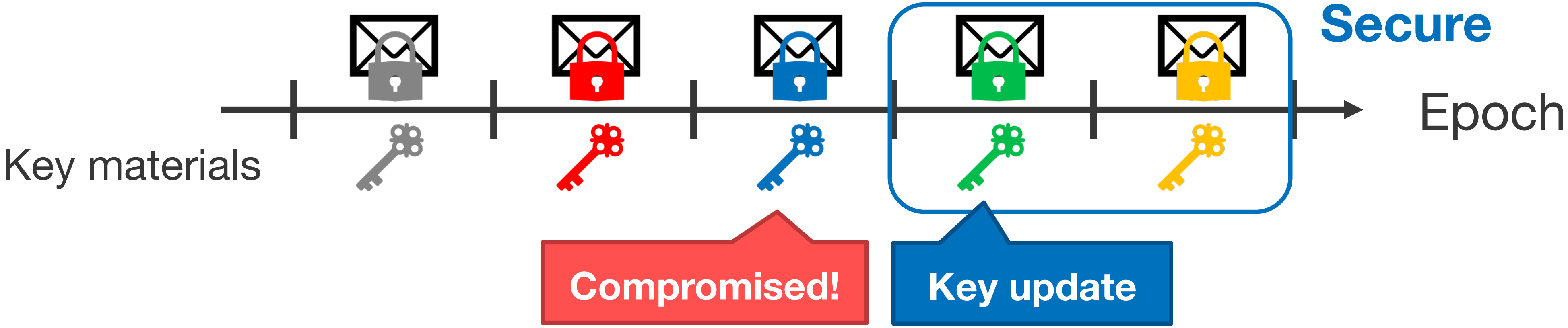
Continuous Group Key Agreement (CGKA) [ACDT20]

CGKA achieves strong security properties by updating key materials

- Forward secrecy (FS)



- Post-compromise security (PCS)



Existing CGKA protocols

- TreeKEM [BBR18, BBN19, ACDT20, ACJM20, AJM20…]
  - Used in IETF Messaging Layer Security (MLS) [OBR+21, BBM+20]
- Chained mKEM [BBN19]
  - Based on multi-recipient PKE (mPKE)
  - Starting point of our study

Bandwidth cost for key update (N: group size)

Scheme	Upload cost	Download cost	Total cost (upload + N-1 download)
TreeKEM	$\Omega(\log N)$	$\Omega(\log N)$	$\Omega(N \log N)$
Chained mKEM	$O(N)$	$O(N)$	$O(N^2)$

Efficient key update is important

As the group size N increases,

- the size of key update messages also increases
- the frequency of key update also increases
  - Likelihood of key compromise is higher for large group

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This tension is amplified by two factors:

- Messaging apps target mobile devices
  - Data cap per month is limited (e.g., 1GB)

- Post-quantum cryptography
  - Consume x10 or more bandwidth than classical counterpart
  - Example: TreeKEM with Classic McEliece [ABC+20] used in 256 users' group.
    If each user updates its key material twice, it costs 1 GB for each user.

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Smaller key update costs are desirable in the real-world!

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Purpose

Design PQ CGKA protocol with small key update costs

Our contribution

Chained CmPKE: CGKA with asymmetric bandwidth cost

Scheme	Upload cost	Download cost	Total cost (upload + N-1 download)
TreeKEM	$\Omega(\log N)$	$\Omega(\log N)$	$\Omega(N \log N)$
Chained mKEM	$O(N)$	$O(N)$	$O(N^2)$
Chained CmPKE	$O(N)^\star$	$\boldsymbol{O(1)}$	$\boldsymbol{O(N)}$

$\star$: When N is about hundreds, the concrete upload cost is smaller than TreeKEM.

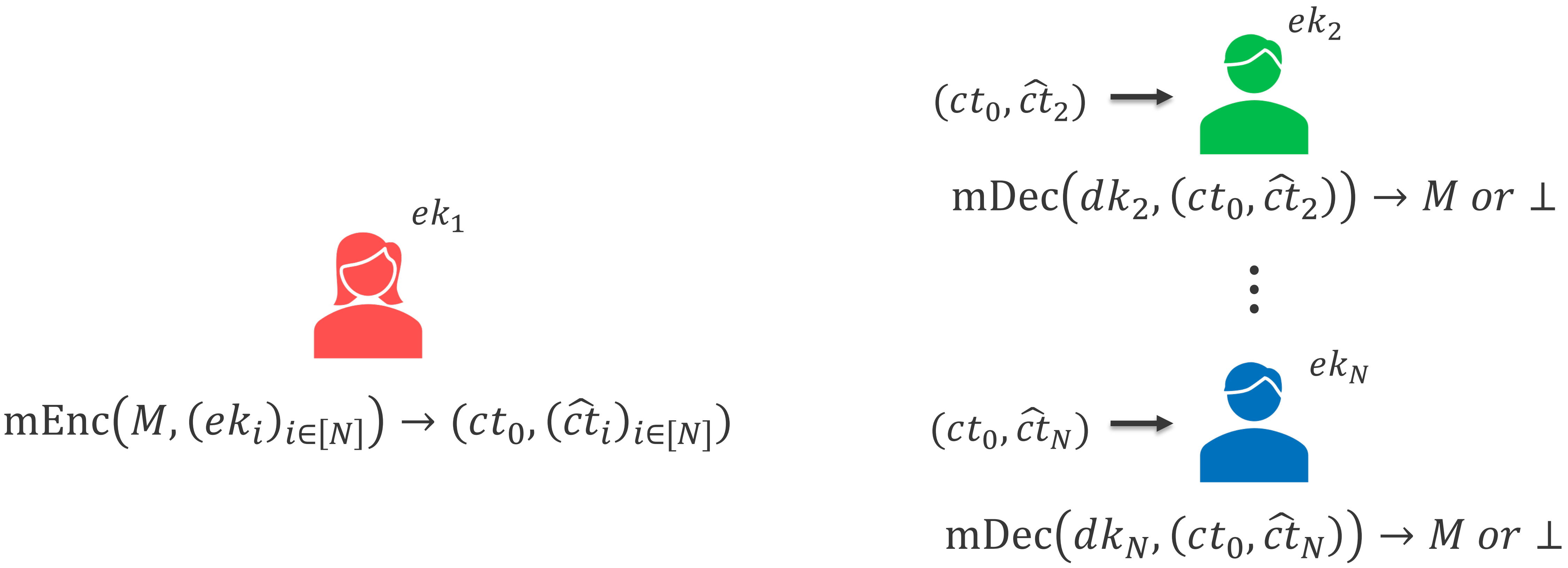
Chained CmPKE is based on Chained mKEM with two new ideas:

1. **Committing mPKE** ⇒ achieve $O(1)$ download cost
2. **More efficient PQ mPKE** ⇒ reduce the concrete size of key update messages

Contribution 1

New CGKA: Chained CmPKE

Racap: Multi-recipient PKE (mPKE)

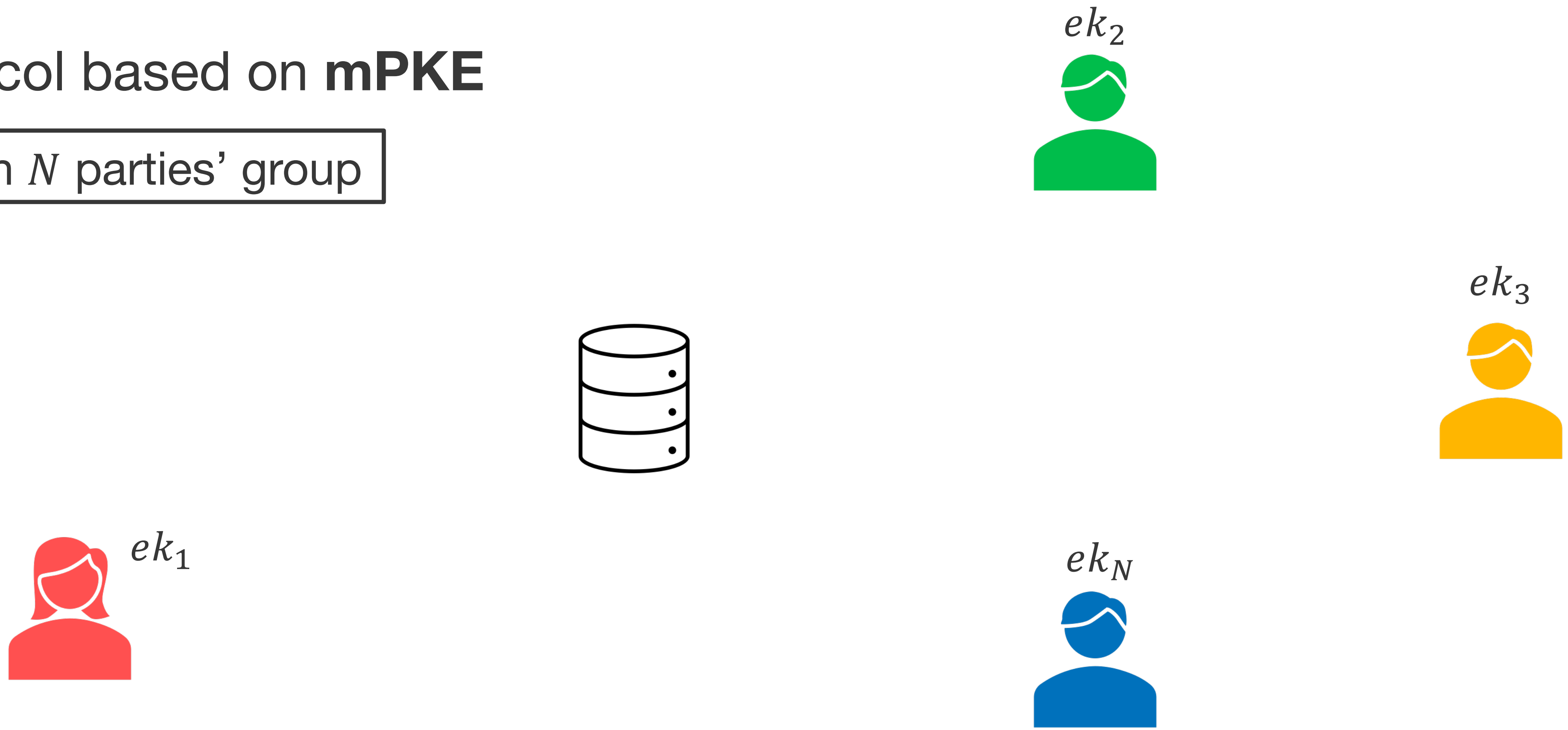


- The same message M can be efficiently encrypted to N parties
- Recently, [KKPP20] has revisited mPKE in the post-quantum setting
  - $|\widehat{ct}_i| \ll |ct_0|$ in this setting

Starting point: Chained mKEM [BBN19]

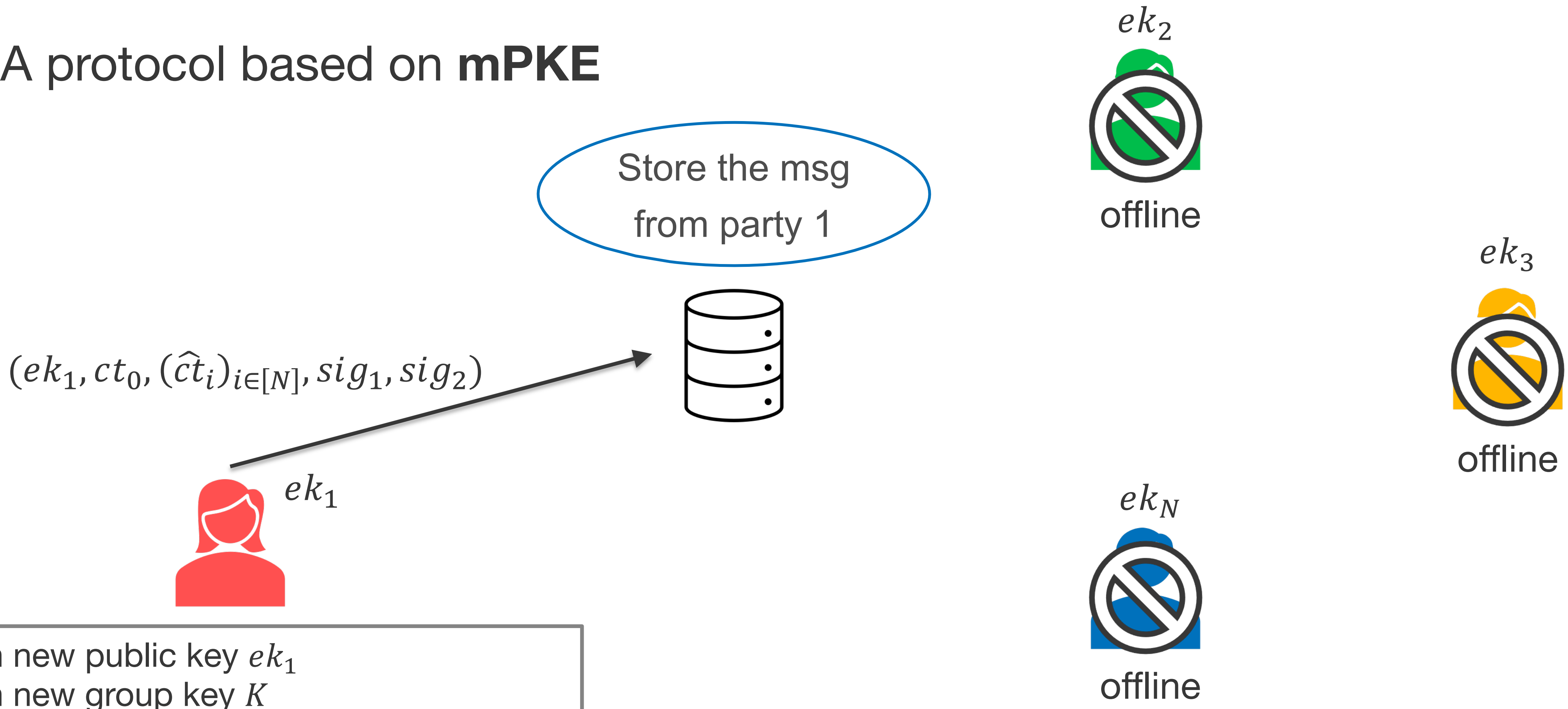
CGKA protocol based on **mPKE**

Key update on N parties' group



Chained mKEM [BBN19]

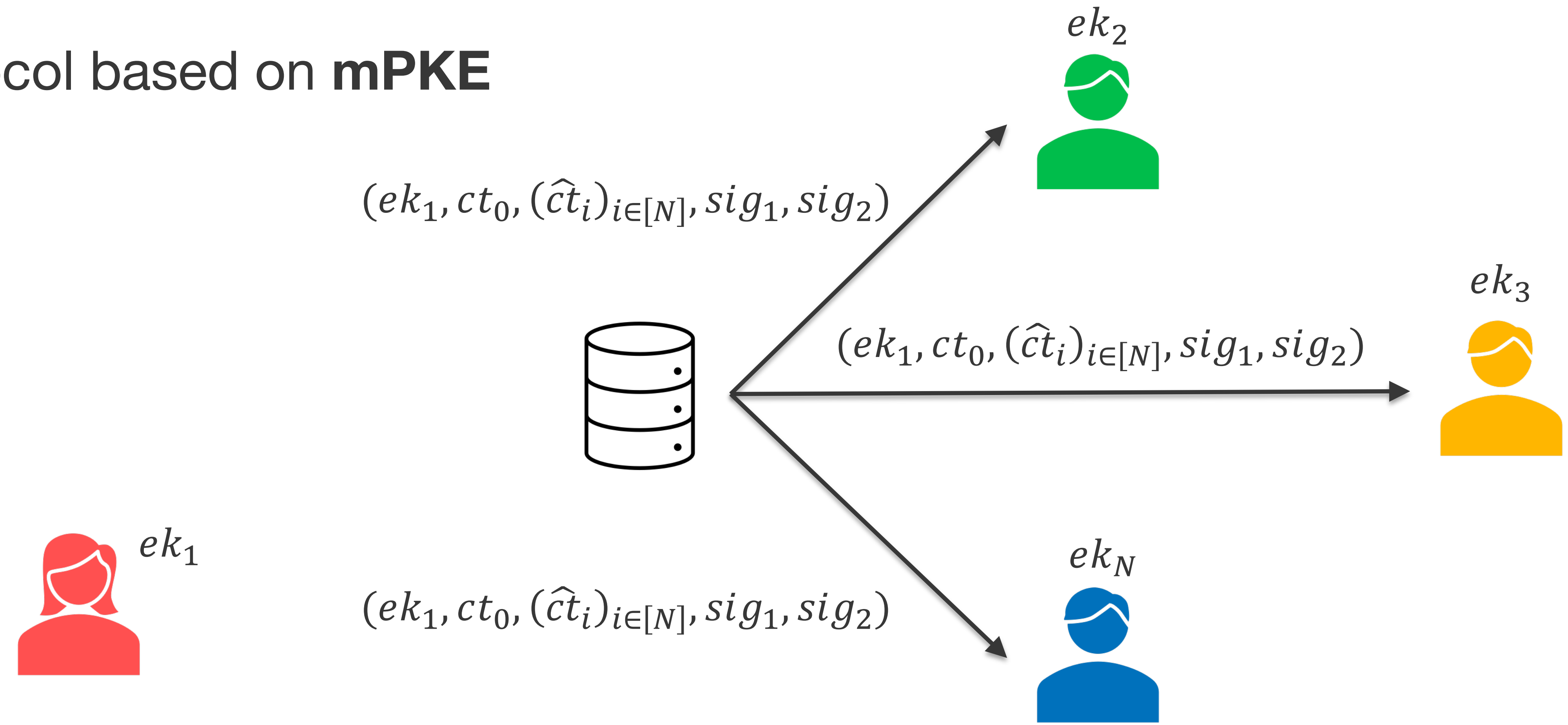
CGKA protocol based on **mPKE**



1. Gen new public key ek_1
2. Gen new group key K
3. Gen $\left(ct_0, (\hat{ct}_i)_{i\in[N]}\right) \leftarrow \text{mEnc}(K, (ek_i)_{i\in[N]})$
4. Gen $sig_1 \leftarrow \text{Sign}(sk_1, ek_1)$
5. Gen $sig_2 \leftarrow \text{Sign}\left(sk_1, (ct_0, (\hat{ct}_i)_{i\in[N]})\right)$

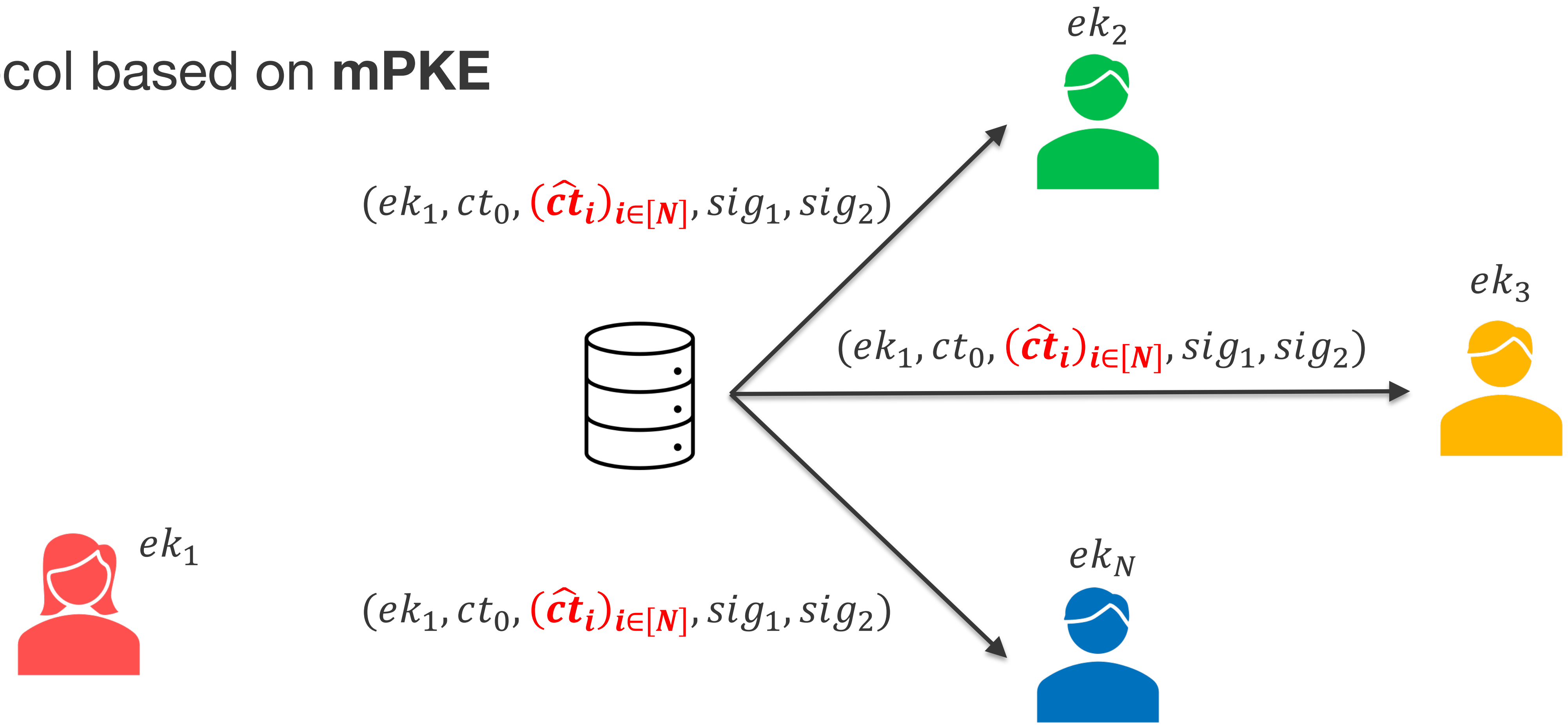
Chained mKEM [BBN19]

CGKA protocol based on **mPKE**



Drawback of Chained mKEM [BBN19]

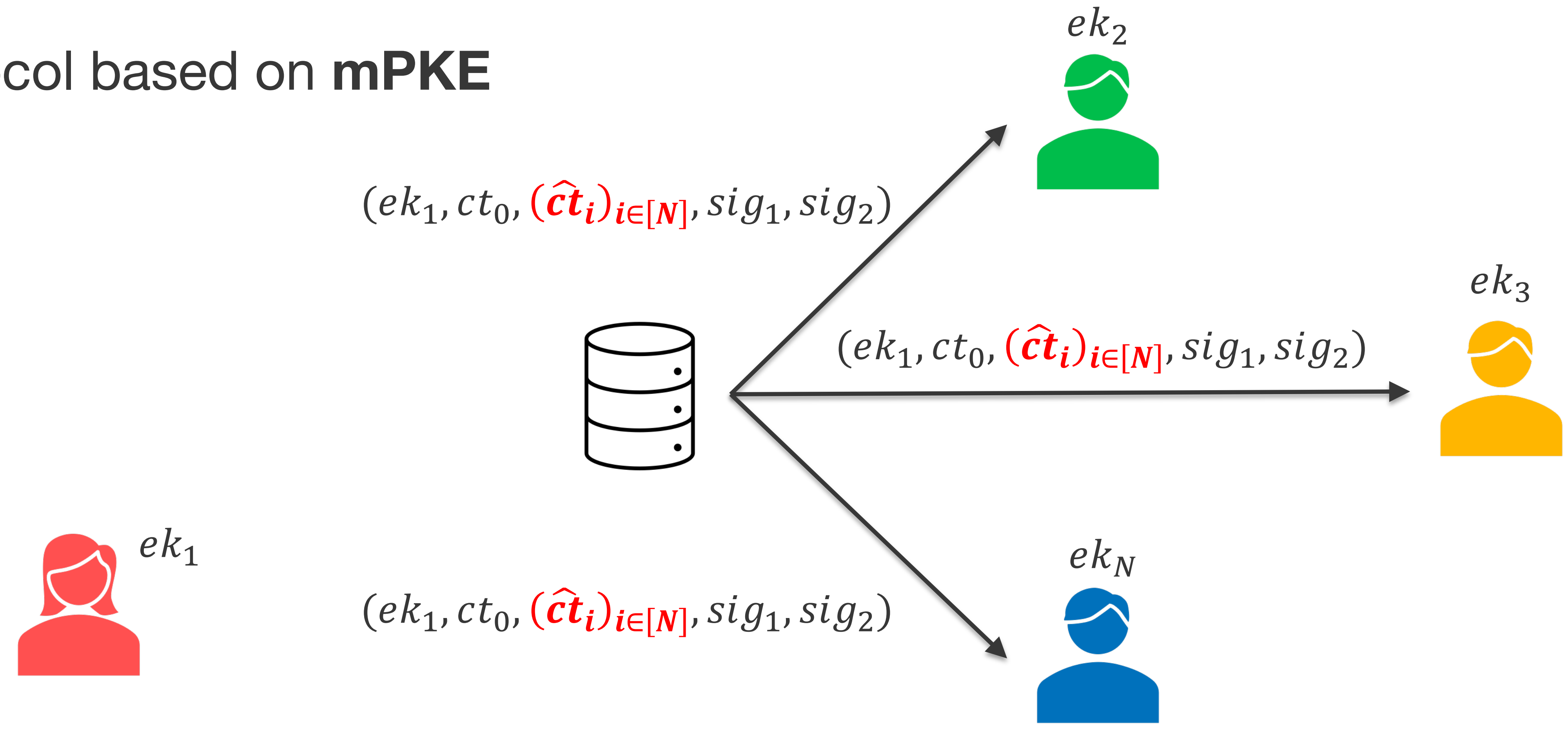
CGKA protocol based on **mPKE**



Download $O(N)$ ciphertexts to verify signature

Drawback of Chained mKEM [BBN19]

CGKA protocol based on **mPKE**

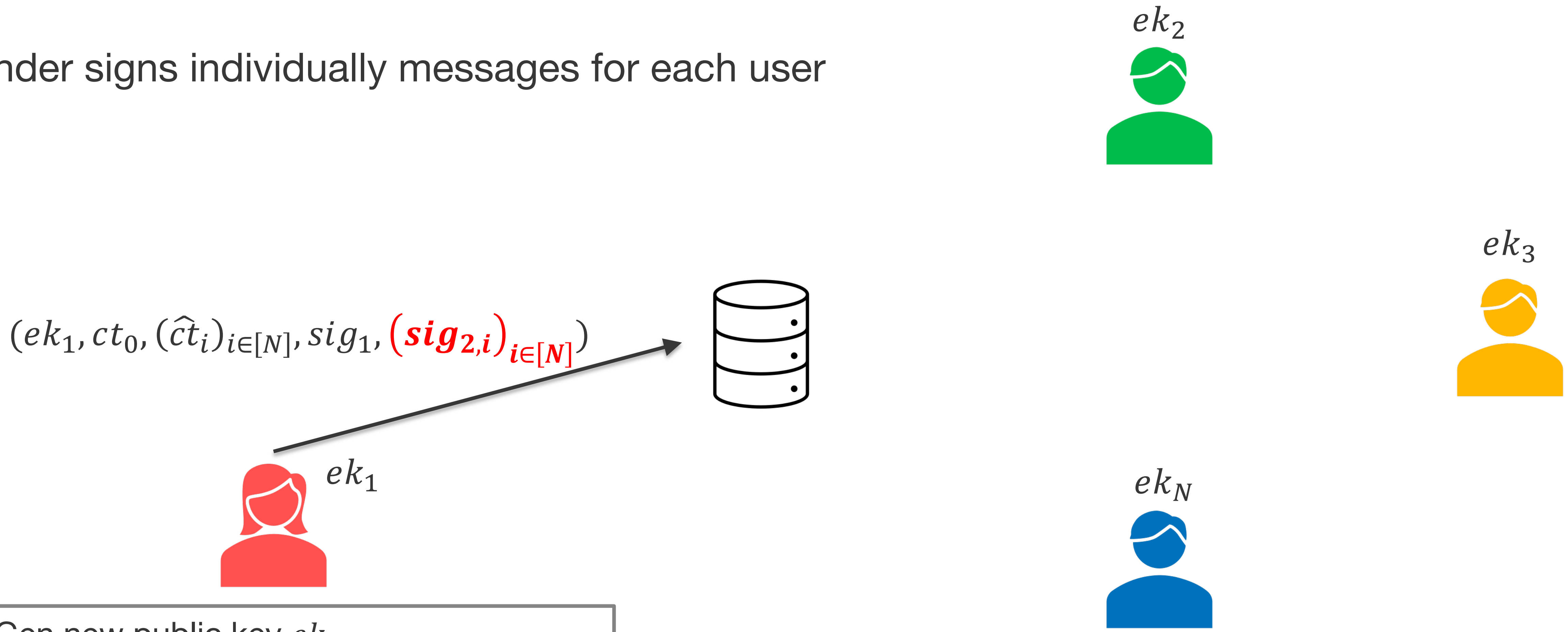


Can we reduce download cost to $O(1)$?

iphertexts
ature

Naïve approach to achieve $O(1)$ download cost

Sender signs individually messages for each user



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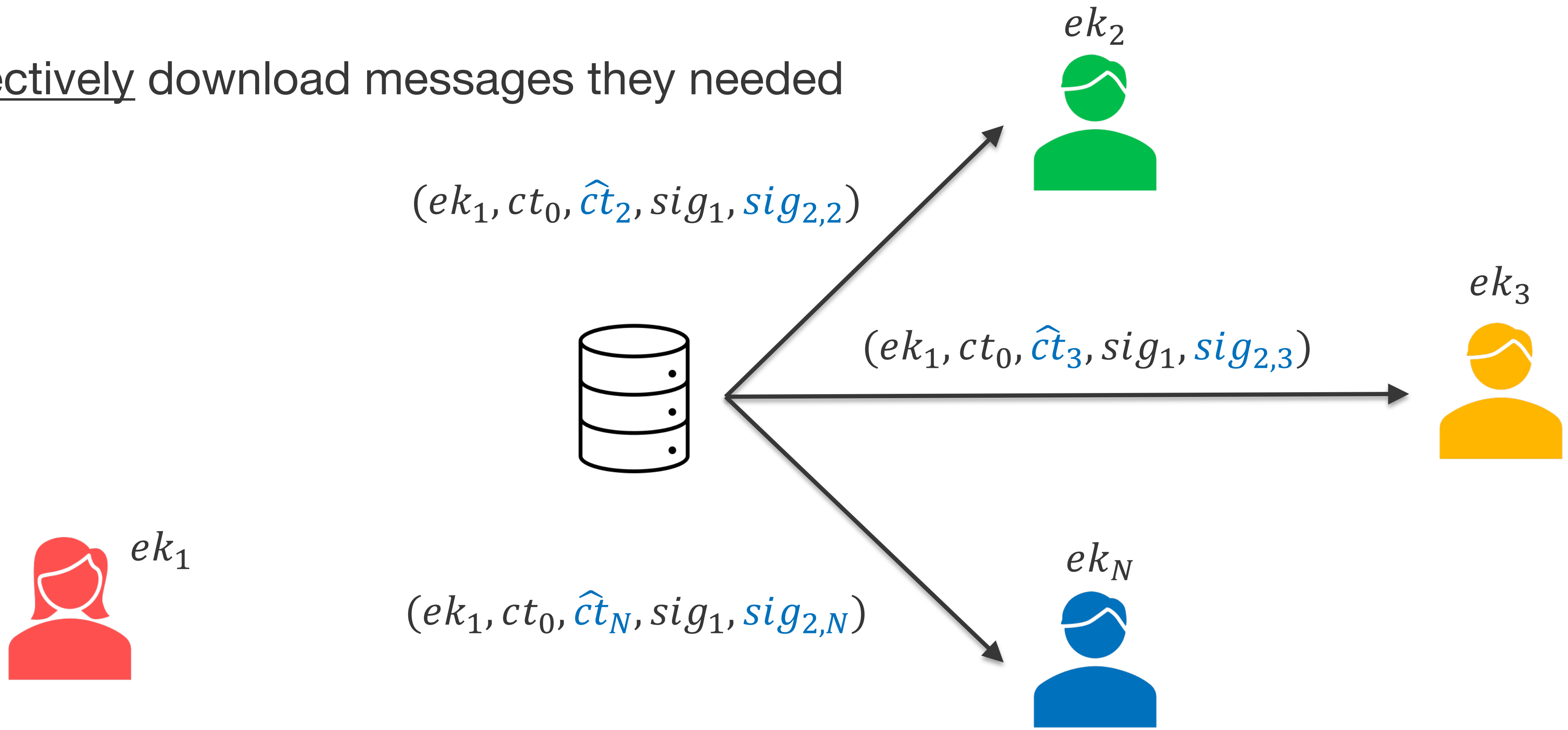
2. Gen new group key K
3. Gen $\left(ct_0, (\hat{ct}_i)_{i\in[N]}\right) \leftarrow \mathrm{mEnc}(K, (ek_i)_{i\in[N]})$
4. Gen $sig_1 \leftarrow \mathrm{Sign}(sk_1, ek_1)$
5. **For $\boldsymbol{i \in [N]}$, $\boldsymbol{sig_{2,i} \leftarrow \mathrm{Sign}(sk_1, (ct_0, \hat{ct}_i))}$**

Naïve approach to achieve $O(1)$ download cost

Recipients selectively download messages they needed



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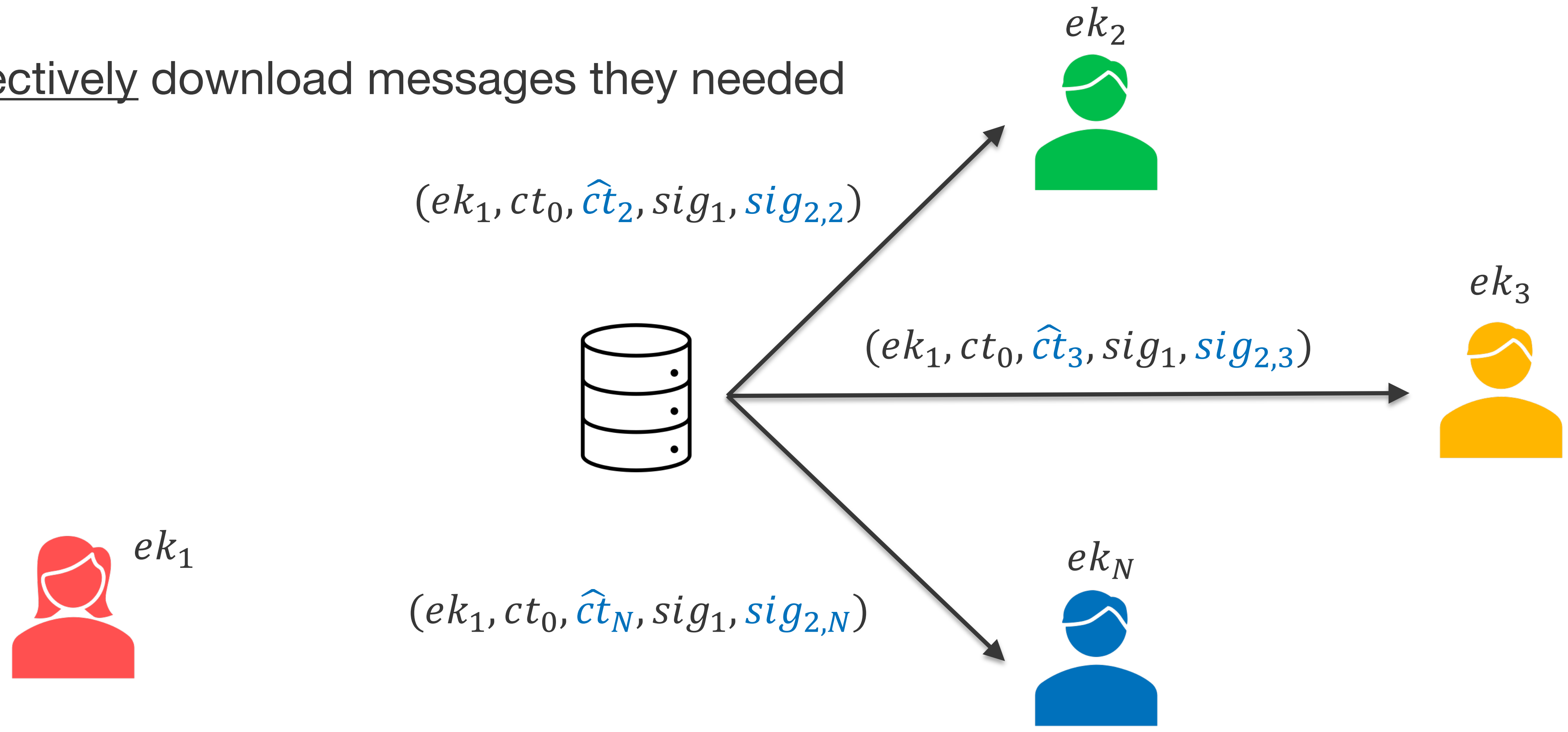

Download cost is $O(1)$

Naïve approach to achieve $O(1)$ download cost

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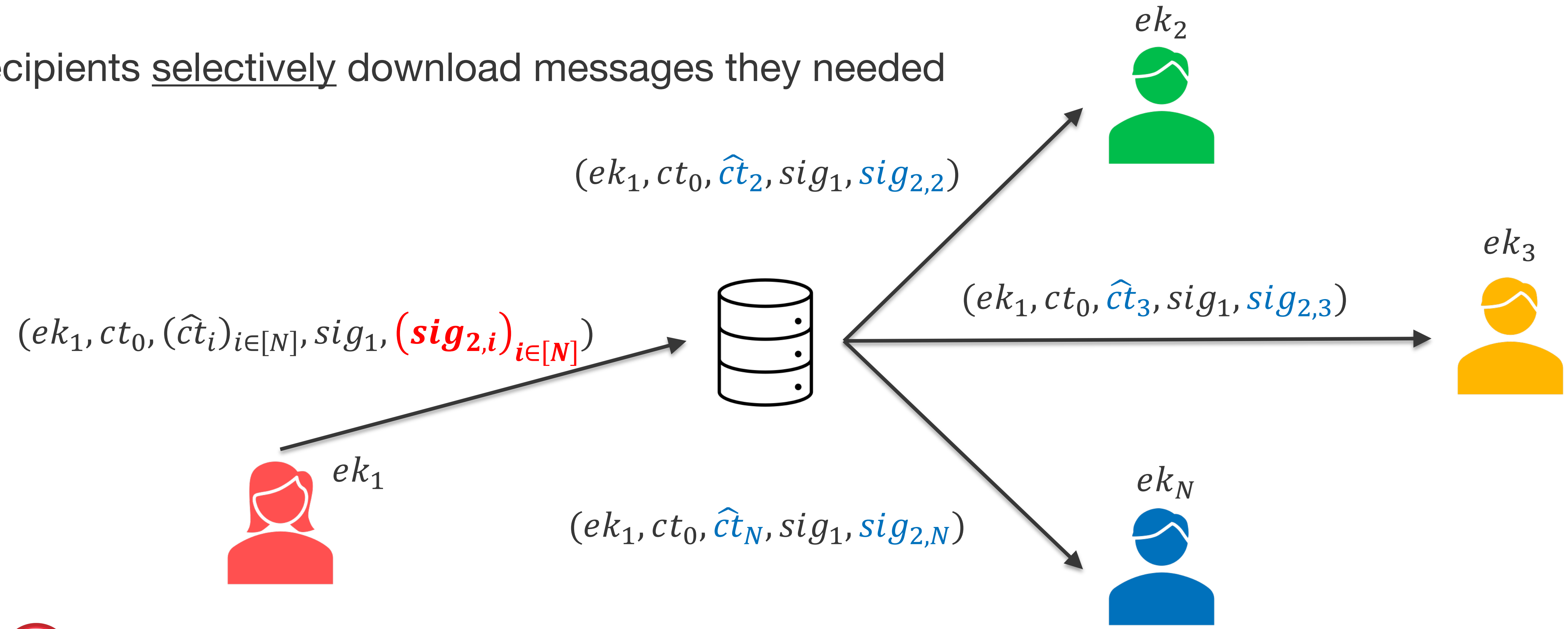


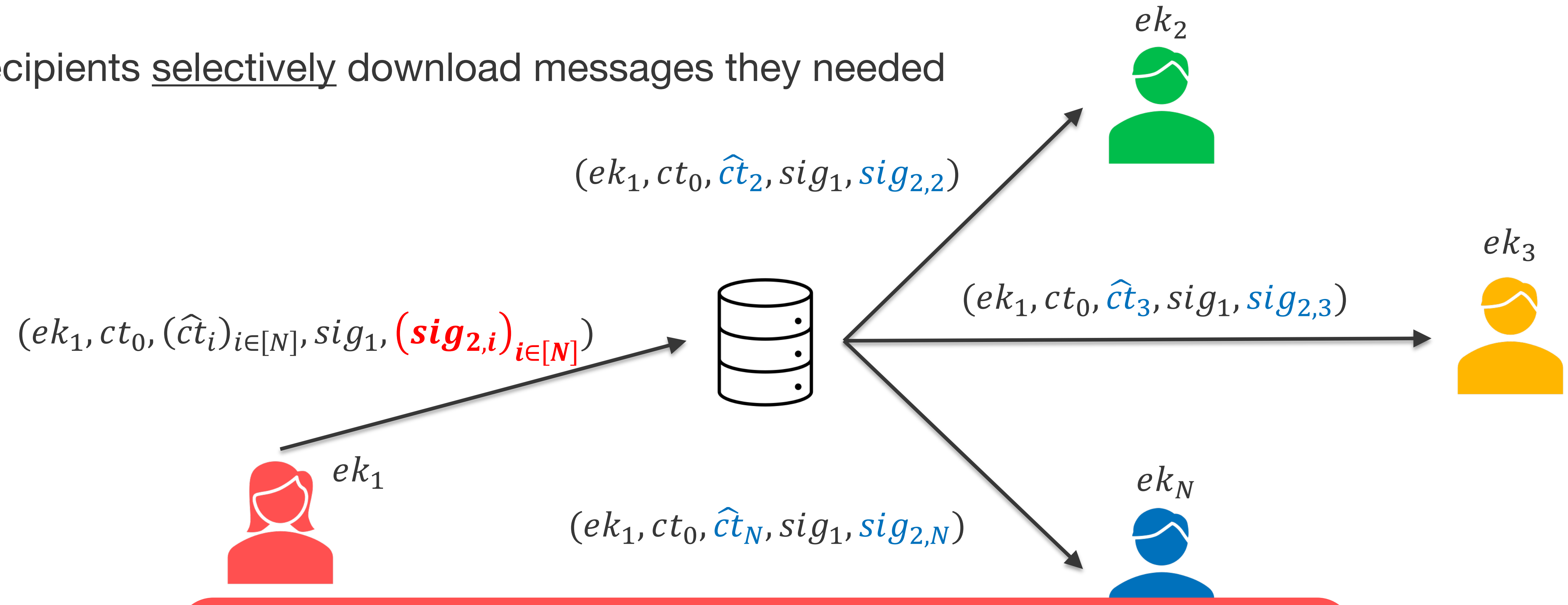
Upload $O(N)$ signatures

Note: PQ signatures are large!

Download cost is $O(1)$

Naïve approach to achieve $O(1)$ download cost

Recipients selectively download messages they needed



Upl

Note: PQ

$\boldsymbol{O(1)}$

Can we reduce download cost to $O(1)$
without increasing the num. of signatures?

Our solution: Committing mPKE (CmPKE)

ek_1

$$\mathrm{CmEnc}\big(M, (ek_i)_{i\in[N]}\big) \rightarrow (\mathrm{T}, (ct_i)_{i\in[N]})$$

ek_2

$(\mathrm{T}, ct_2) \rightarrow$

$$\mathrm{CmDec}\big(dk_2, (\mathrm{T}, ct_2)\big) \rightarrow M \text{ or } \perp$$

⋮

ek_N

$(\mathrm{T}, ct_N) \rightarrow$

$$\mathrm{CmDec}\big(dk_N, (\mathrm{T}, ct_N)\big) \rightarrow M \text{ or } \perp$$

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$\mathrm{CmEnc}\big(M, (ek_i)_{i\in[N]}\big) \to (\mathrm{T}, (ct_i)_{i\in[N]})$

ek_2

(T, ct_2) → 

$\mathrm{CmDec}\big(dk_2, (\mathrm{T}, ct_2)\big) \to M \text{ or } \bot$

⋮

ek_N

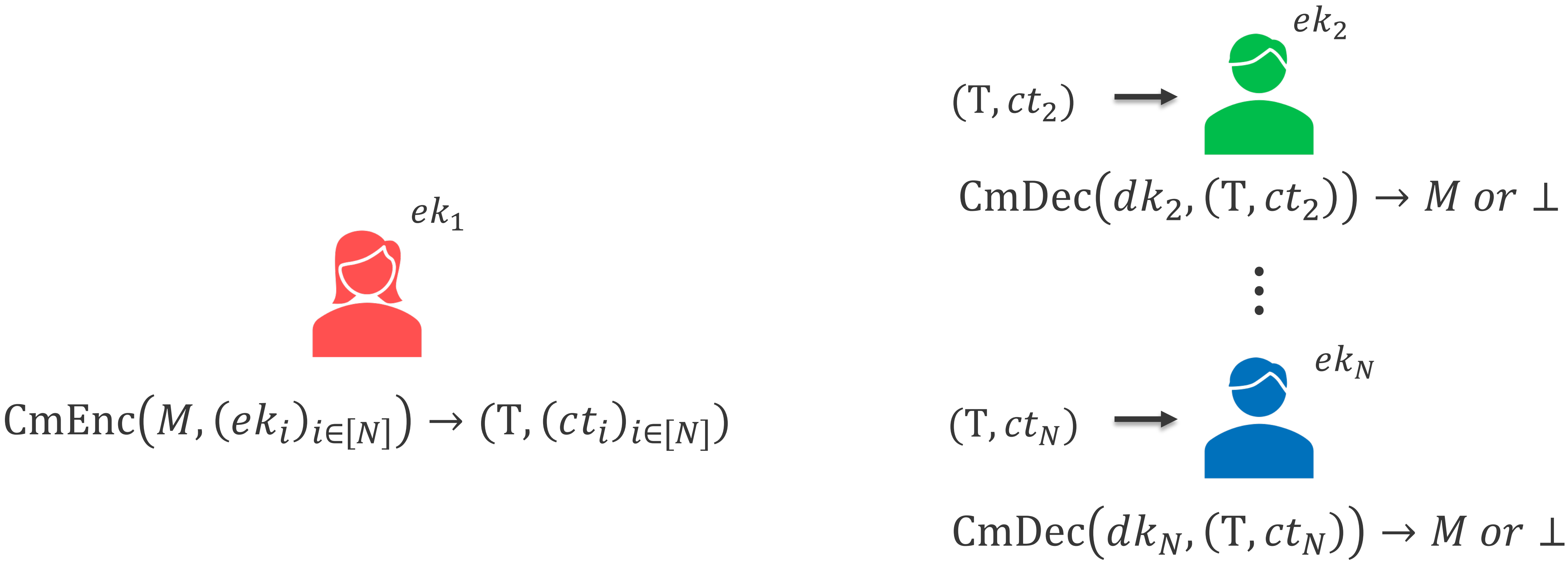
(T, ct_N) → 

$\mathrm{CmDec}\big(dk_N, (\mathrm{T}, ct_N)\big) \to M \text{ or } \bot$

Commitment-binding: T is linked to a unique message M

⇒ If parties receive the same T, they decrypt the same M or $\bot$

Our solution: Committing mPKE (CmPKE)



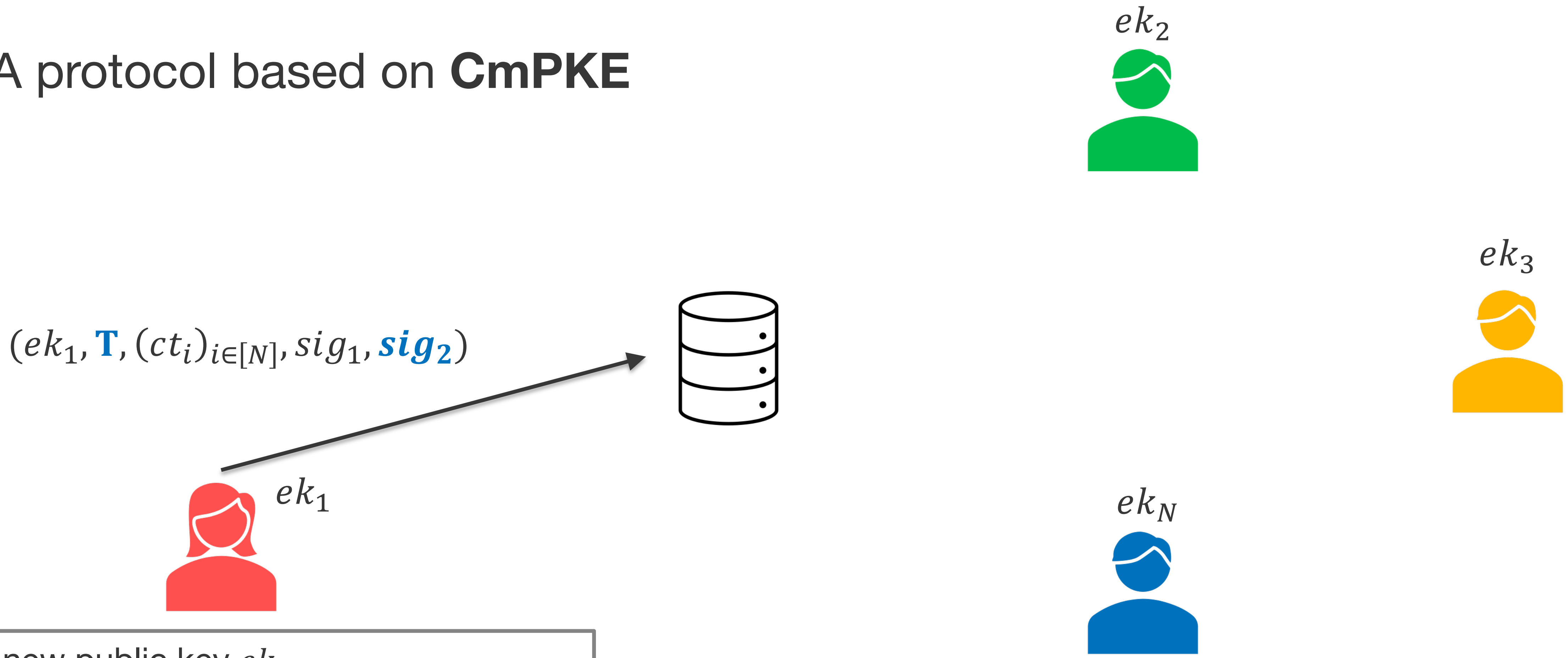
Propose IND-CPA mPKE ⇒ IND-CCA CmPKE transformation

- CmEnc runs $\mathrm{mEnc}\big(k, (ek_i)_{i \in [N]}\big) \rightarrow (\mathrm{ct}_0, (\widehat{ct}_i)_{i \in [N]})$ and $\mathrm{SKE.Enc}(k, M) \rightarrow c$
- Outputs $\mathrm{T} = (ct_0, c)$ and $ct_i = \widehat{ct}_i$, $|c| = 32$ bytes

Use key-committing AEADs [FOR17, GLR17, ADG+20] as SKE

Our CGKA: Chained CmPKE

CGKA protocol based on **CmPKE**



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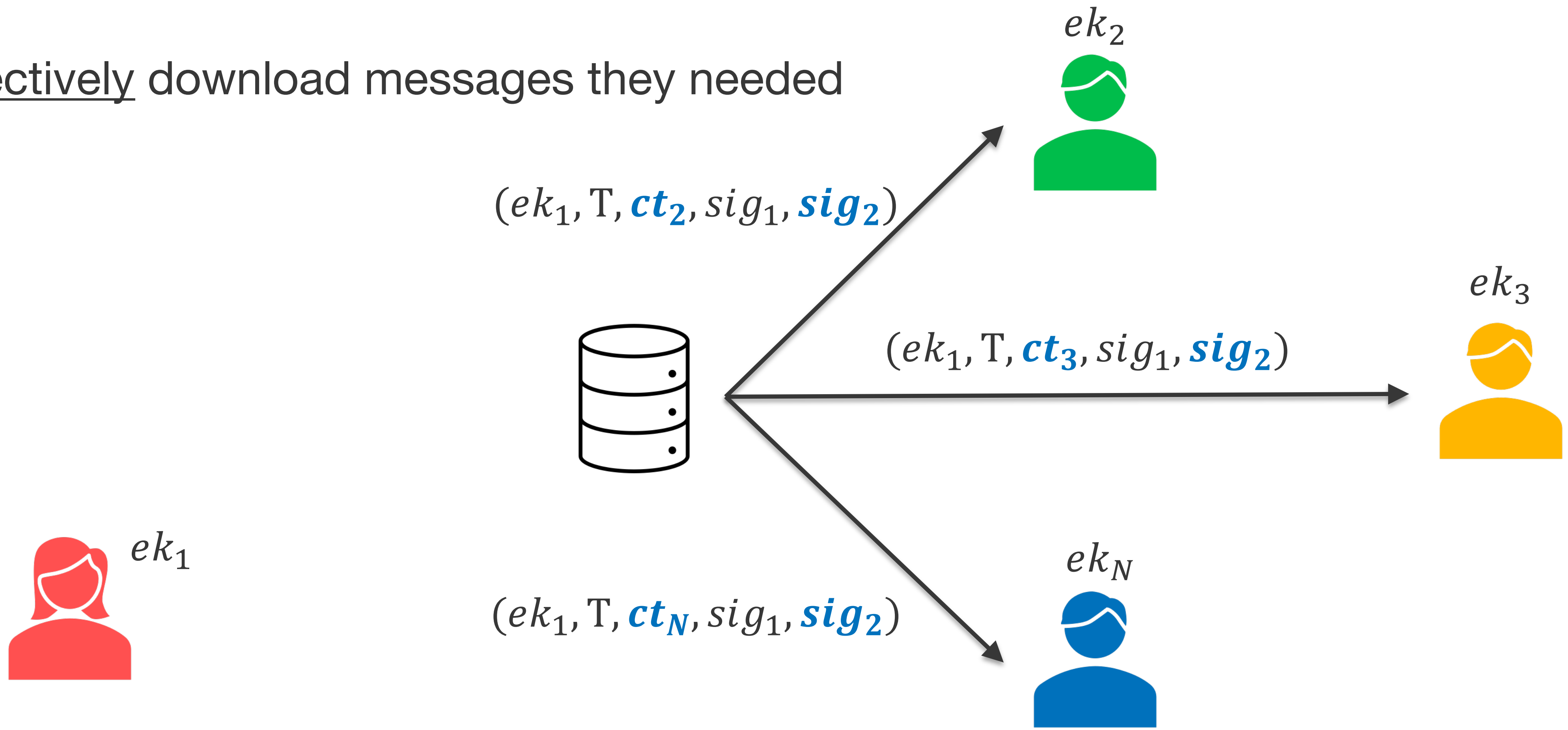
4. Gen $sig_1 \leftarrow \mathrm{Sign}(sk_1, ek_1)$
5. **Gen $\boldsymbol{sig_2} \leftarrow \mathbf{Sign}(\boldsymbol{sk_1}, \mathbf{T})$**

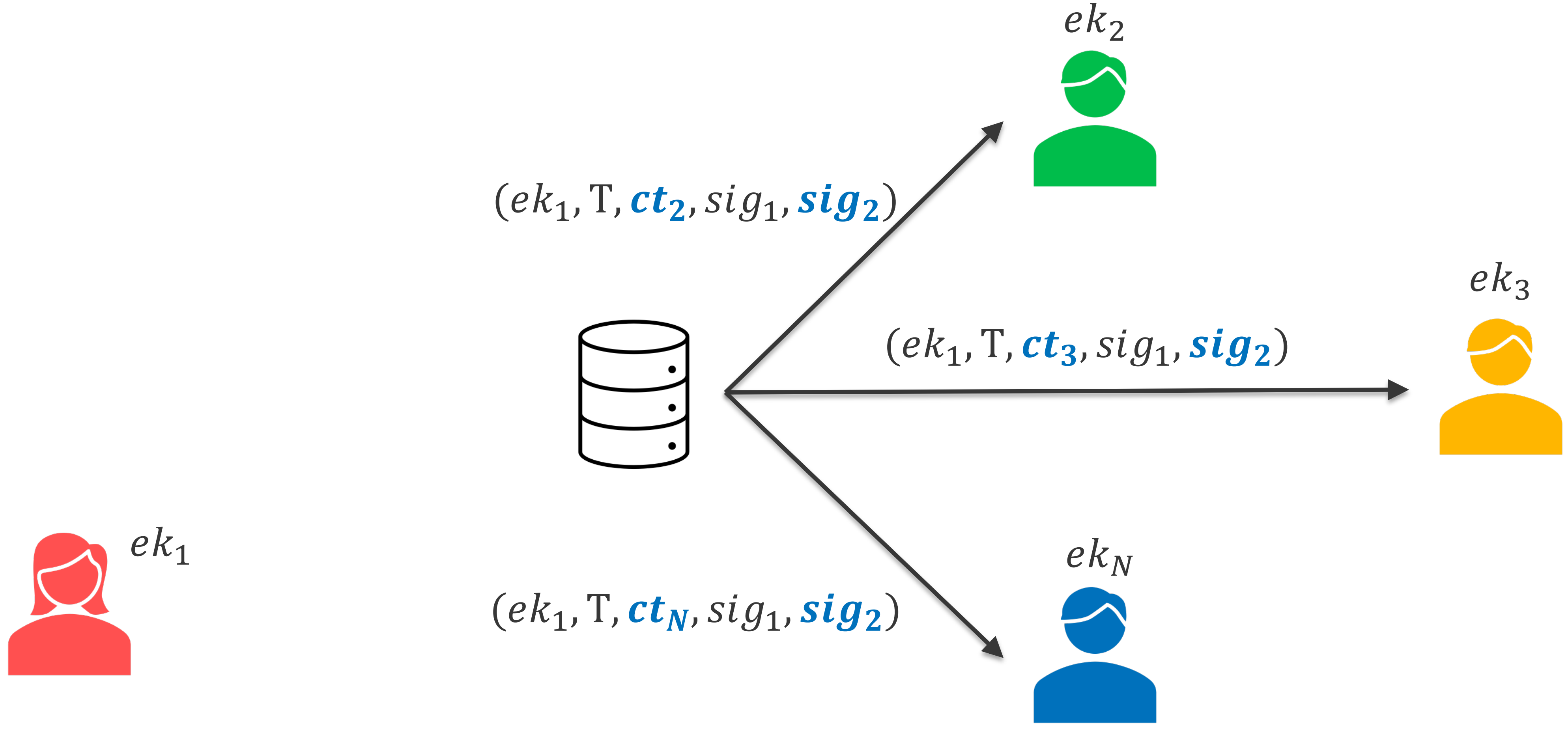
Due to commitment-binding, tampering with ct_i is detected at decryption

Our CGKA: Chained CmPKE

Recipients selectively download messages they needed

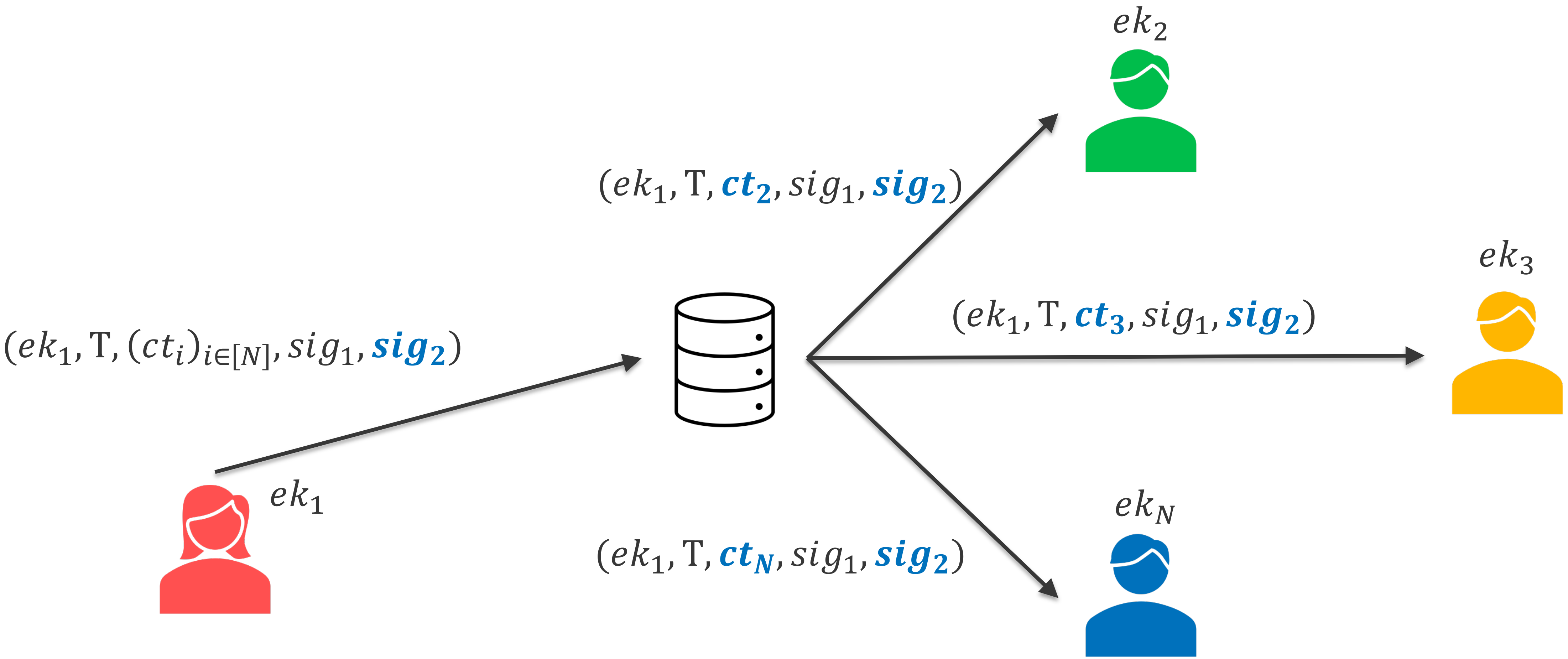


Our CGKA: Chained CmPKE



Download cost is $O(1)$

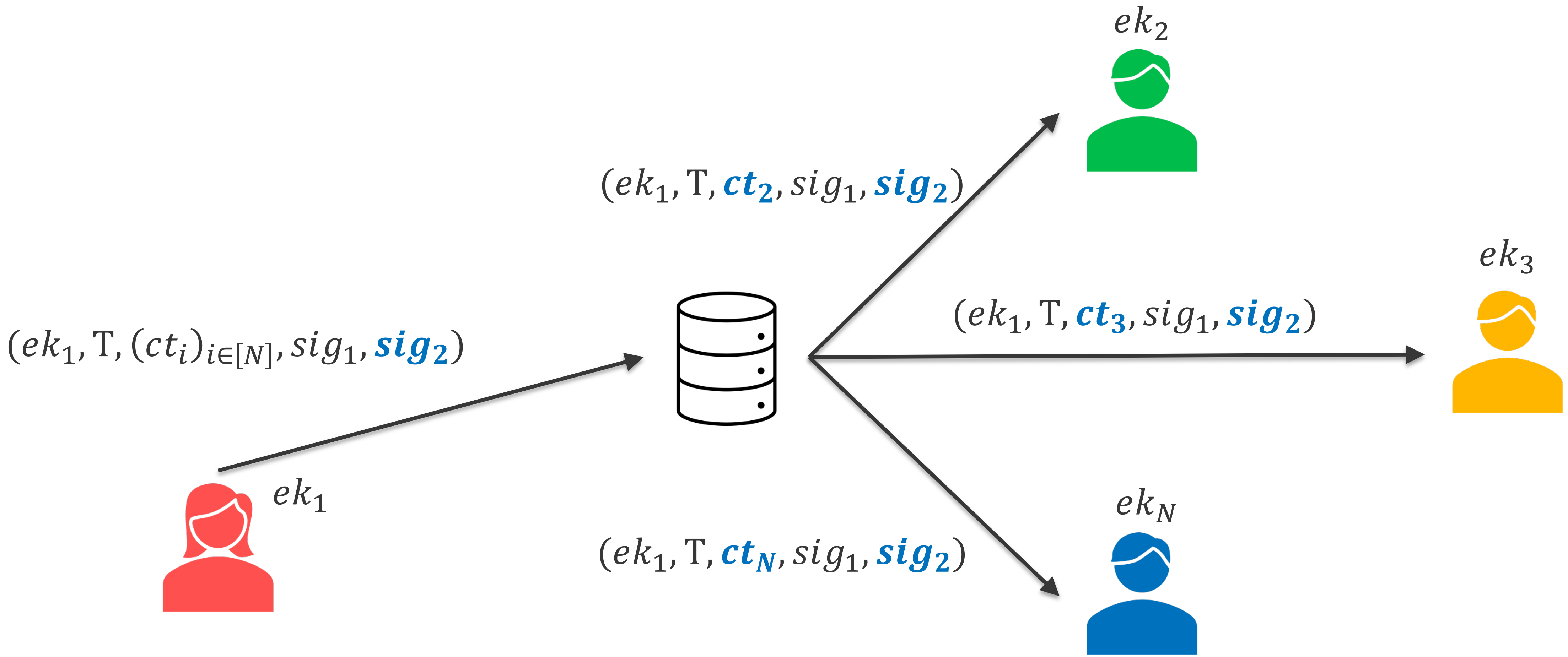
Our CGKA: Chained CmPKE



✅ **Upload constant signatures**

✅ **Download cost is $O(1)$**

Our CGKA: Chained CmPKE



Upl ... (1)

We achieve $O(1)$ download cost without increasing the num. of signatures! ☺

Security of Chained CmPKE

Chained CmPKE is as secure as TreeKEM version 10 in MLS

- Adopt the UC security model in [AJM20] used to analyze TreeKEM
  - It considers active adversaries and malicious insiders
- Extend this model to capture selective downloading of messages
  - Our model is the strict generalization of the model in [AJM20]

Contribution 2

More efficient post-quantum mPKEs

Existing post-quantum mPKE

[KKPP20] proposed efficient PQ mPKEs based on LWE, LWR, and SIDH.
Example scheme based on [LPR10, LP11]:

$\mathrm{Enc}(ek = \mathbf{B}, M)$:

1. Sample short matrixes $\mathbf{R}, \mathbf{E}', \mathbf{E}''$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. $\mathbf{V} \leftarrow \mathbf{RB} + \mathbf{E}'' + \mathrm{Encode}(M)$
4. $ct \coloneqq (\mathbf{U}, \mathbf{V})$

→

$\mathrm{mEnc}(\{ek_1, \dots, ek_N\}, M)$:

1. Sample short matrixes $\mathbf{R}, \mathbf{E}'$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. For $i = 1, \dots, N$
   1. Sample short matrix $\mathbf{E}_i''$
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4. $(ct_0, (\widehat{ct}_i)_{i \in [N]}) \coloneqq (\mathbf{U}, (\mathbf{V}_i)_{i \in [N]})$

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Two shortcomings of [KKPP20]:
1. Not optimize parameters to make $\widehat{ct}_i$ smaller
    - In CGKA setting, small $\widehat{ct}_i$ is desirable to reduce upload cost ($\sim |\widehat{ct}_i| \cdot N$)
2. Not analyze the hardness of underlying problems in mPKE setting

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Two shortcomings of [KKPP20]:

1. No
   - …N)
2. No

We fix this two shortcomings ☺

Designing Lattice-Based mPKEs: Attacks and Toolkit

- **Attacks with $O(1)$ samples**
  - Lattice (primal)
  - Lattice (dual)
  - Decoding

- **Attacks with many samples**
  - Arora-Ge: requires $n^{O(d)}$ samples (d = cardinality of error support)
  - BKW

- **Toolkit**
  - *Bit dropping*
    + \+ Decrease $|\mathbf{V}_i|$
    + \+ Increase the LWE noise
    + – Increase decryption failure
  - *Coefficient dropping*
    + \+ Decrease $|\mathbf{V}_i|$
  - *Increase the modulus q*
    + \+ Pack more bits / coefficient
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Designing Lattice-Based mPKEs: Attacks and Toolkit

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Good for security!

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Comparison: new parameters vs. existing parameters

Bandwidth of mPKE based on existing parameters (blue) and new parameters (blank)

Size in byte. Security level is NIST I (≧ AES-128).

mPKE scheme	$\lvert ek \rvert$	$\lvert ct_0 \rvert$	$\lvert \widehat{ct_i} \rvert$
Kyber512 [SAB+ 20]	768(+32)	640	128
Ilum512	768	704	**48**
LPRime653 [BBC+ 20]	865(+32)	865(+32)	128
LPRime757	1076	1076	**32**
Frodo640 [NAB+ 20]	9600(+16)	9600	120
Bilbo640	10240	10240	**24**
SIKEp434 [JAC+ 20]	330	330	16

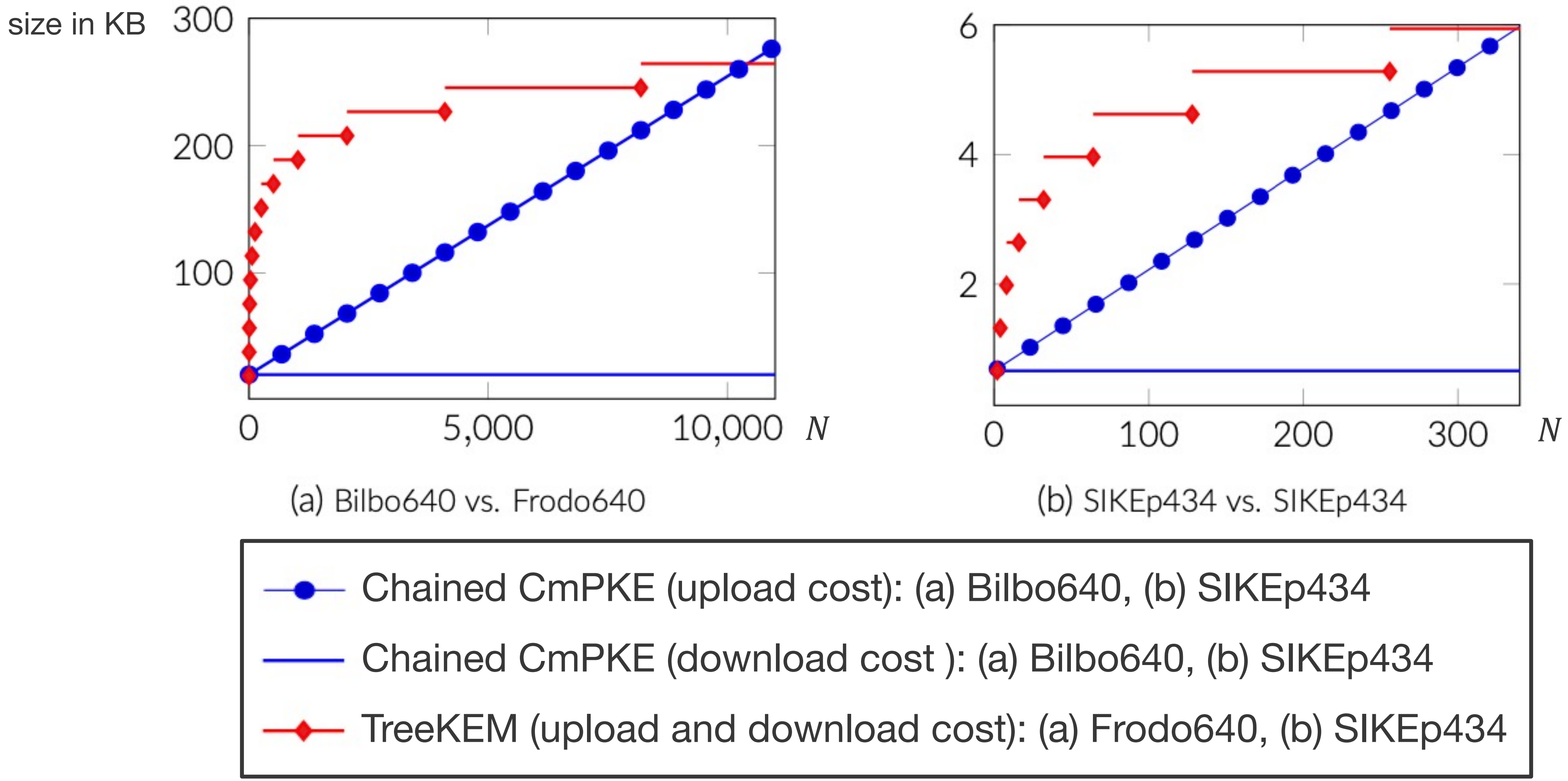
$\lvert \widehat{ct_i} \rvert$ is reduced by 60-80% at the cost of slightly increase in $\lvert ek \rvert$ and $\lvert ct_0 \rvert$

⇒ Minimize the concrete size of key update messages ($\sim \lvert \widehat{ct_i} \rvert \cdot N$)

Comparison and Implementation

Chained CmPKE vs. TreeKEM: upload and download cost

Size of key update messages in Kilobyte (y-axis) depending on the group size (x-axis)

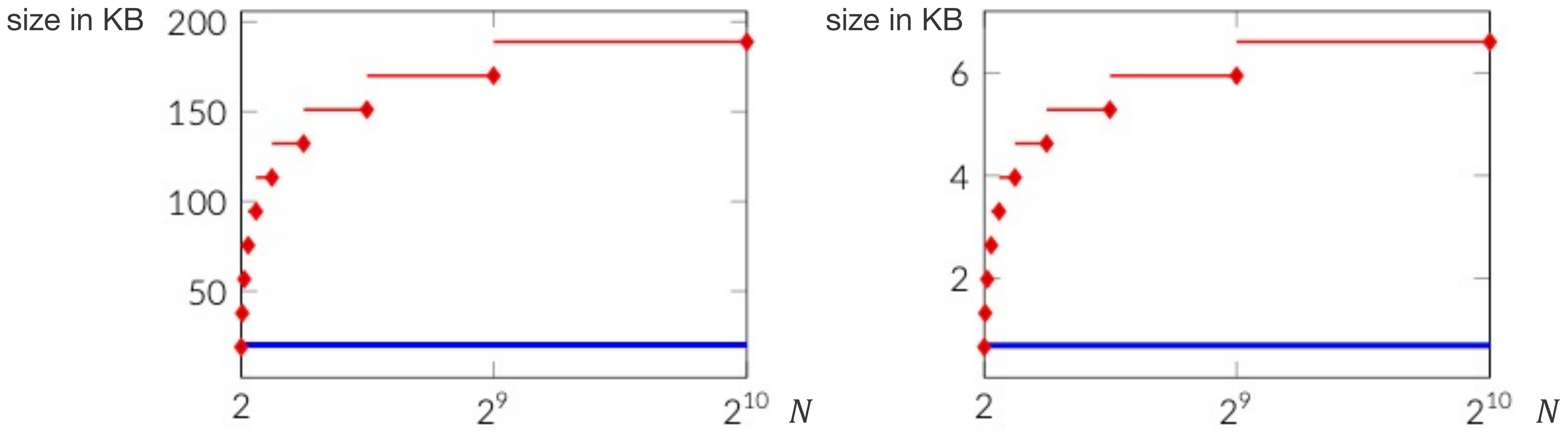


(a) Bilbo640 vs. Frodo640

(b) SIKEp434 vs. SIKEp434

Chained CmPKE vs. TreeKEM: total cost (normalized by N)

Total cost of key update in Kilobyte (y-axis) depending on the group size N (x-axis)



(a) Bilbo640 vs. Frodo640

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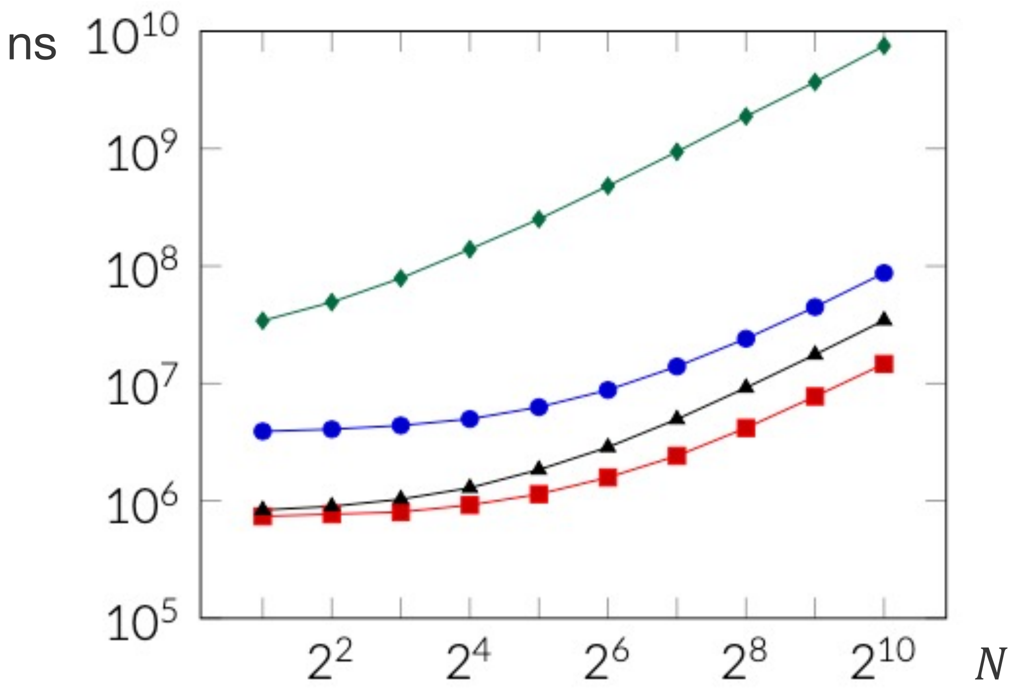
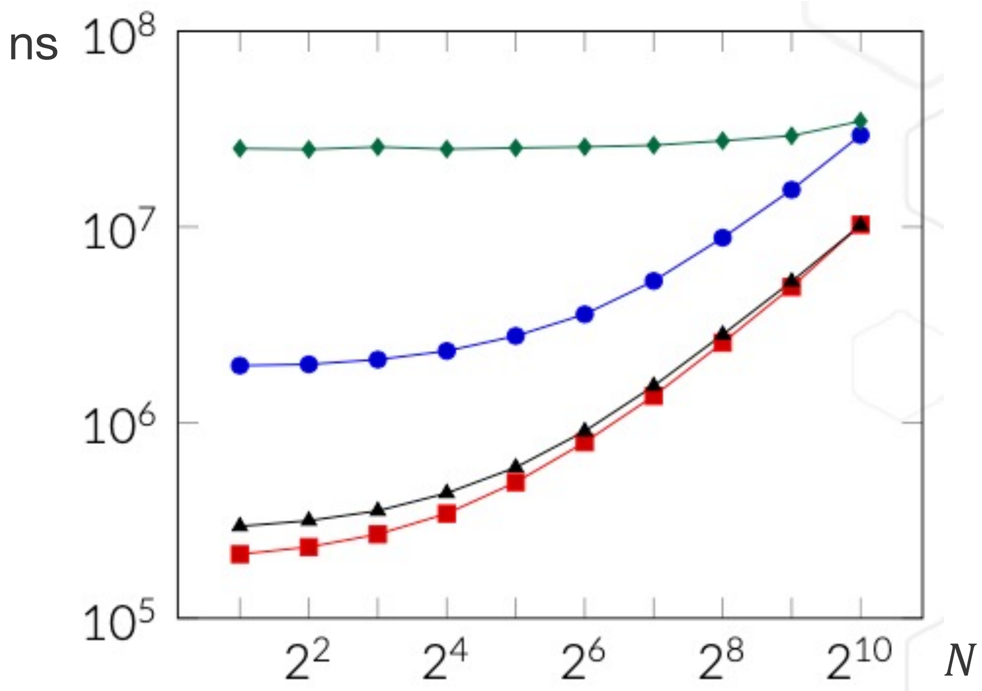
Chained CmPKE: computation cost



(a) Generate key update messages



(b) Process received messages

Execution time in nanoseconds of some procedures as a function of group size for Ilum512 (red square), LPRime757 (black triangle), Bilbo640 (blue circle), SIKEp434 (green diamond).
Log-scale. Times are obtained on Apple M1@3.2 GHz.

Conclusion

Chained CmPKE: CGKA with asymmetric bandwidth cost

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TreeKEM	$\Omega(\log N)$	$\Omega(\log N)$	$\Omega(N \log N)$
Chained mKEM	$O(N)$	$O(N)$	$O(N^2)$
Chained CmPKE	$O(N)^\star$	$\boldsymbol{O(1)}$	$\boldsymbol{O(N)}$

$\star$: When N is about hundreds, the concrete upload cost is smaller than TreeKEM.

Chained CmPKE is based on Chained mKEM with two new ideas:

1. **Committing mPKE** ⇒ achieve $O(1)$ download cost
2. **More efficient PQ mPKE** ⇒ reduce the size of key update messages

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