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

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Séminaire de Cryptographie de l'Université de Rennes 1

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Full paper: `https://eprint.iacr.org/2021/1407`

Why Secure Messaging?

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Secure messaging applications are widespread...

WhatsApp	2.5 Billions
Facebook Messenger	1.3 Billions
Telegram	500 Millions
Snapchat	280 Millions

...and represent attractive targets for attackers:

- "*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
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- etc.

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- etc.

This talk: the security of secure *group* messaging *protocols*

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Specific constraints:

→ Asynchrony

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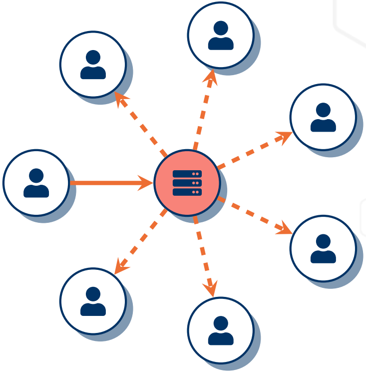
- Large number of users ($N \gg 1$)



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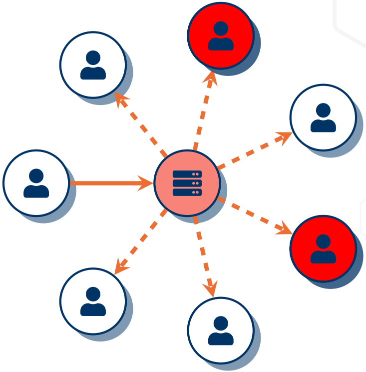
- Minimise trust in the server ($\Longrightarrow$ end-to-end encryption)
- Large number of users ($N \gg 1$)
- Very long sessions ($t \gg 1$)



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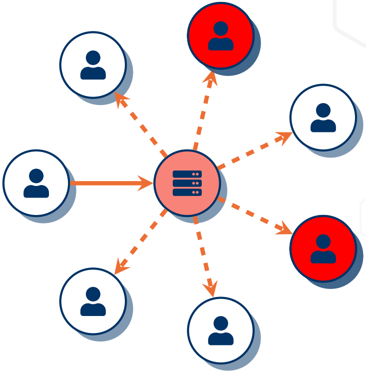
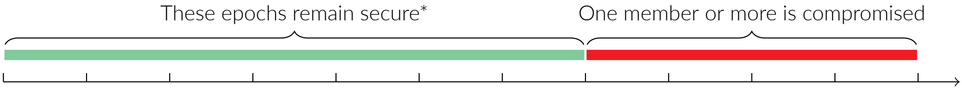


If each user has a probability ϵ of being compromised by an attacker during a unit of time, a group conversation with N members over t units of time will be compromised with probability $1 - (1 - \epsilon)^{Nt}$.

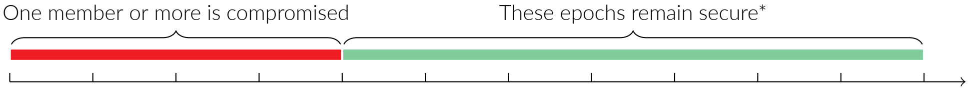
- This probability is significant as soon as $Nt = \Omega(1/\epsilon)$.
- **Solution:** periodically refresh encryption keys (next slides).

Some security notions

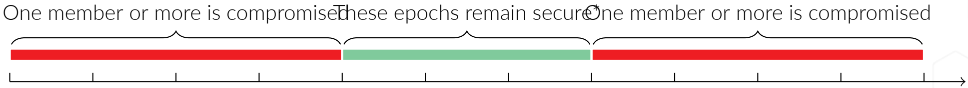
Forward secrecy (FS) [CCG16, CGCD^{+}17, ACD19]:



Post-Compromise Security (PCS) [CCG16, CGCD^{+}17, ACD19]:



Post-Compromise Forward Security (PCFS) [ACDT20, ACJM20, AJM20]:



CGKAs

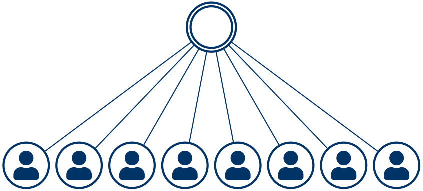
CGKAs (*Continuous Group Key Agreement*) concentrate the cryptographic mechanisms of secure gorup messaging protocols:

- → Add a user
- → Remove a user
- → **Remove one's encryption keypair (*Ratcheting/Commit Message*)**

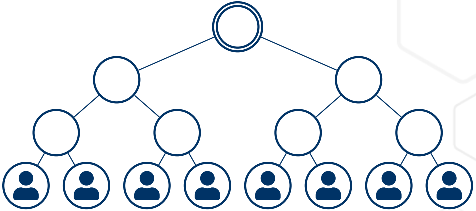
Prominent CGKAs:

- → *Pairwise Channels* (Signal)
- → *Sender Keys* (WhatsApp)
- → *TreeKEM* [BBR18, Wei19, BBN19, ACDT20, AJM20, ACJM20, ACC$^+$21] (IETF MLS draft standard [OBR$^+$21, BBM$^+$20])
- → *Chained mKEM* [BBN19]

Chained mKEM



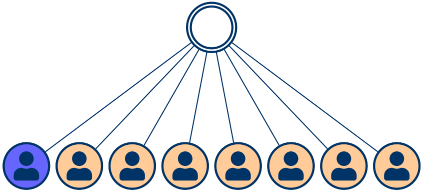
TreeKEM



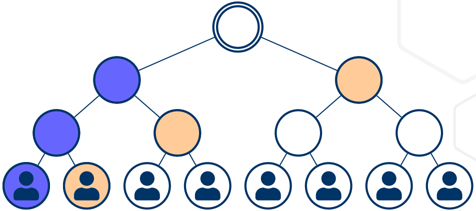
In Chained mKEM and TreeKEM:

- → To each node (○,◎) is associated an encryption keypair
- → A user knows the decryption key of a node if and only if this node is in their path (i.e. the node is an ancestor of the user's node)

Chained mKEM



TreeKEM

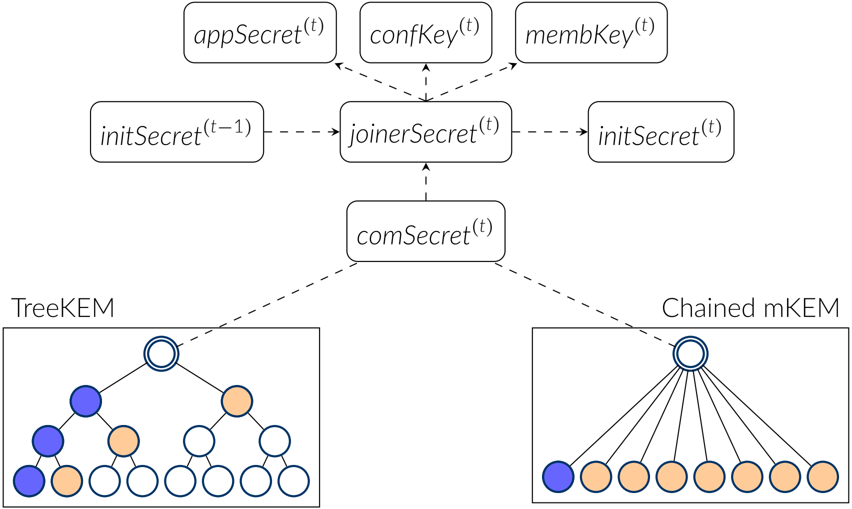


In Chained mKEM and TreeKEM:

- → To each node (◯,◎) is associated an encryption keypair
- → A user knows the decryption key of a node if and only if this node is in their path (i.e. the node is an ancestor of the user's node)
- → A commit message (here, sent by the leftmost user) contains:
  - › an encryption key for each
  - › an asymmetric ciphertext for each
  - › two signatures (one that authenticates encryption keys, one that authenticates ciphertext)

Therefore it has a size $O(N)$ for Chained mKEM, and $\Omega(\log N)$ for TreeKEM.

A change of epoch $(t-1) \longrightarrow t$



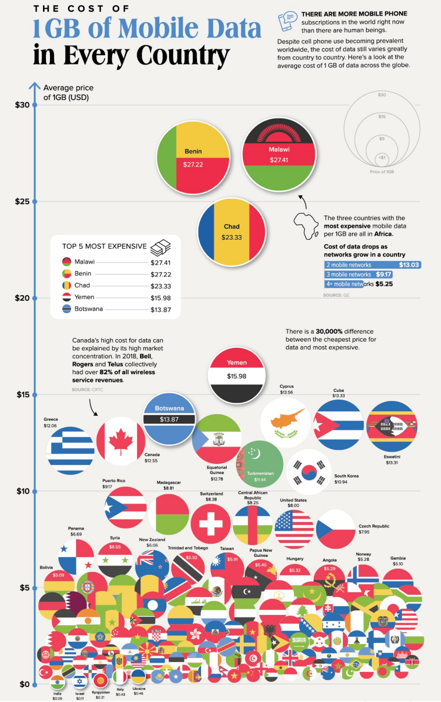
The larger a group size N is, the more *commit messages*:

- are necessary
- are costly

This tension is amplified by:

- the cost and impact for end users
- post-quantum cryptography ($\times 10$ or more compared to classical cryptography). Example with:
  - TreeKEM
  - Classic McEliece [ABC+20]
  - 256 users

  If each user sends one *commit message*, the bandwidth cost if 512 MiB per user.



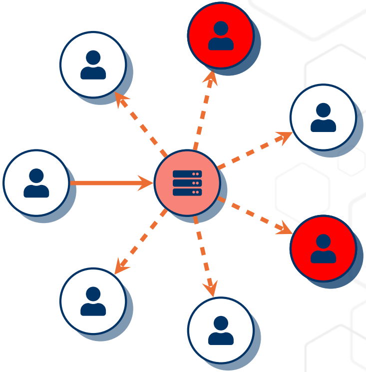
([1])

[1] https://www.visualcapitalist.com/cost-of-mobile-data-worldwide/

Our solution

Chained CmPKE, un CGKA avec un coût asymétrique en envoi et réception (de *commit message*):

	Upload	Download	Total
Chained CmPKE	$O(N)$	$O(1)$	$O(N)$
TreeKEM	$\Omega(\log N)$	$\Omega(\log N)$	$\Omega(N \log N)$



Conceptually, the main change of Chained CmPKE is to make the server more active (but without entrusting it more).

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

1. **Use very efficient mPKEs (*multi-recipient PKE*)** $\Rightarrow$ reduce upload costs
2. **The use of CmPKE (*committing mPKE*)** $\Rightarrow$ a cost $O(1)$

Ingredient №1: *Committing* mPKEs

Committing mPKEs

Syntax of a mPKE (*multi-recipient PKE*):

- $\mathsf{mEnc}(\mathtt{M}, (\mathtt{ek}_i)_{i \in [N]}) \to (\mathtt{ct}_0, (\widehat{\mathtt{ct}}_i)_{i \in [N]})$
- $\mathsf{mDec}(\mathtt{dk}_i, (\mathtt{ct}_0, \widehat{\mathtt{ct}}_i)) \to \{\mathtt{M} \text{ or } \perp\}$

Recently revisited in [KKPP20], which inspired this work.

The syntax of a CmPKE (*committing mPKE*) is identical:

- $\mathsf{CmEnc}(\mathtt{M}, (\mathtt{ek}_i)_{i \in [N]}) \to (\mathsf{T}, (\mathtt{ct}_i)_{i \in [N]})$
- $\mathsf{CmDec}(\mathtt{dk}_i, (\mathsf{T}, \mathtt{ct}_i)) \to \{\mathtt{M} \text{ or } \perp\}$

In addition, we require that T is *committing*, i.e. T is bound to a unique message $\mathtt{M}$. A related notion: *committing AEADs* [GLR17]

We provide an (mPKE IND-CPA $\Rightarrow$ CmPKE IND-CCA) transform, with:

- $\mathtt{ct}_i = \widehat{\mathtt{ct}}_i$.
- $\mathsf{T} = (\mathtt{ct}_0, c)$ and $|c| = 32$ bytes.

Our transform uses *key-committing AEADs* [FOR17, GLR17, ADG+20].

Impact of CmPKEs

In Chained mKEM, a commit message contains:

1. A new encryption key $\mathtt{ek}$
2. An mPKE ciphertext: $(\mathtt{ct}_0, (\widehat{\mathtt{ct}}_i)_{i \in [N]})$
3. A signature $\mathtt{sig}_1 \leftarrow \mathsf{Sign}(\mathtt{sk}, \mathtt{ek})$
4. A signature $\mathtt{sig}_2 \leftarrow \mathsf{Sign}(\mathtt{sk}, (\mathtt{ct}_0, (\widehat{\mathtt{ct}}_i)_{i \in [N]}))$

In Chained CmPKE, a commit message contains:

Upload:

1. $\mathtt{ek}$
2. A CmPKE ciphertext: $(\mathsf{T}, (\mathtt{ct}_i)_{i \in [N]})$
3. $\mathtt{sig}_1 \leftarrow \mathsf{Sign}(\mathtt{sk}, \mathtt{ek})$
4. $\mathtt{sig}_2 \leftarrow \mathsf{Sign}(\mathtt{sk}, \mathsf{T})$

Download:

1. $\mathtt{ek}$
2. $(\mathsf{T}, \mathtt{ct}_i)$
3. $\mathtt{sig}_1$
4. $\mathtt{sig}_2$

Intuitively, any attempt from the server to tamper with T or $\mathtt{ct}_i$ is detected upon signature verification or during decryption.

Ingredient №2: more efficient mPKEs

Post-quantum mPKEs

[KKPP20] highlighted the existence of very efficient mPKEs based on LWE, LWR and SIDH. Exemple with LPR-style schemes [LPR10, LP11]:

$\mathsf{Enc}(\mathbf{ek} = \mathsf{B}, \mathtt{M})$

1. Sample short matrices $\mathbf{R}, \mathbf{E}', \mathbf{E}''$
2. $\mathbf{U} \leftarrow \mathbf{RA} + \mathbf{E}'$
3. $\mathbf{V} \leftarrow \mathbf{RB} + \mathbf{E}'' + \mathsf{Encode}(\mathtt{M})$
4. $\mathtt{ct} := (\mathbf{U}, \mathbf{V})$

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4. $\mathtt{ct} := (\mathbf{U}, \mathbf{V})$

$\Longrightarrow$

$\mathsf{mEnc}(\{\mathbf{ek}_1, \ldots, \mathbf{ek}_N\}, \mathtt{M})$

1. Sample short matrices $\mathbf{R}, \mathbf{E}'$
2. $\mathbf{U} \leftarrow \mathbf{R}\mathbf{A} + \mathbf{E}'$
3. For $i = 1, \ldots, N$:
   1. Sample a short matrix $\mathbf{E}''_i$
   2. $\mathbf{V}_i \leftarrow \mathbf{R}\mathbf{B}_i + \mathbf{E}''_i + \mathsf{Encode}(\mathtt{M})$
4. $\left(\mathtt{ct}_0, (\widehat{\mathtt{ct}}_i)_{i \in [N]}\right) := (\mathbf{U}, (\mathbf{V}_i)_{i \in [N]})$

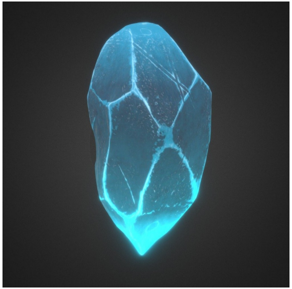
Limitations of [KKPP20]:

- Naive parametrisations
- No concrete security analysis

We propose three re-parametrisations of lattice-based (m)PKEs:

BilboKEM640 (inspired form FrodoKEM640)

Ilum512 (inspired from Kyber512)



LPR757 (inspired from NTRU LPR653)

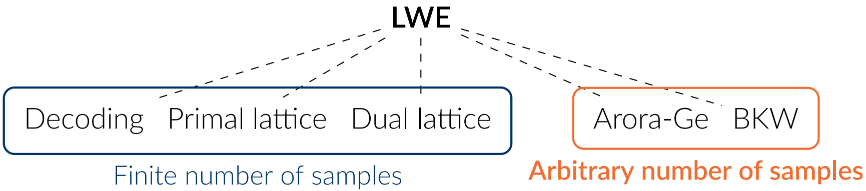
These mPKEs are tailored for the Chained CmPKE protocol:

- → The $(\widehat{\mathtt{ct}}_i)_{i \in [N]}$ are extremely small
- → This entails a small increase of the sizes of $\mathtt{ek}$ and $\mathtt{ct}_0$

Recall that $\mathtt{M} = \mathrm{Decode}(\mathbf{V}_i - \mathsf{dk}_i \cdot \mathbf{U})$. Our toolkit:

- **Bit dropping:** cut the least significant bits of $\mathbf{V}_i$
  - Reduces the size of $\mathbf{V}_i$, increases the LWEv error rate
  - Increases the *decryption failure rate*
- **Coefficent dropping:** cut superflous coefficients of $\mathbf{V}$
  - Reduces the size of $\mathbf{V}_i$
  - None!
- **Increase the modulus** q
  - Allows to pack more bits of key per coefficient of $\mathbf{V}_i$
  - Increases the size of $\mathbf{U}$, reduces the LWE error rate
- **Error correcting codes** (discarded option)
  - Reduces the decryption failure rate
  - Timing attacks, delicate security analysis [DVV19, GJY19, DTVV19]

The main attacks to (re-)consider:



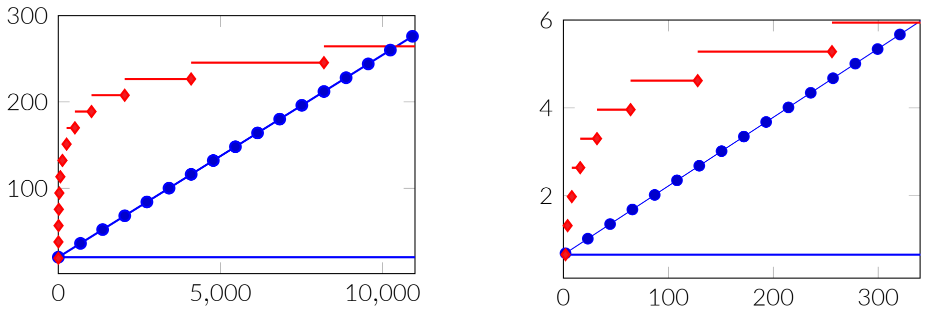
Communication costs of mPKEs based on existing (gray background) and new (fond blanc) parametrisations. Sécurité: NIST I ($\geq$ AES-128).

Schéma	$\lvert\mathtt{ek}\rvert$	$\lvert\mathtt{ct}_0\rvert$	$\lvert\widehat{\mathbf{ct}}_i\rvert$
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**

Comparisons & Conclusion

Chained CmPKE vs TreeKEM (upload and download)

Size of a commit message in KiB as a function of the group size.



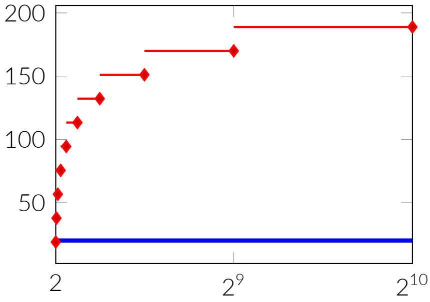
(a) Bilbo640 vs. Frodo640

(b) SIKEp434 vs. SIKEp434

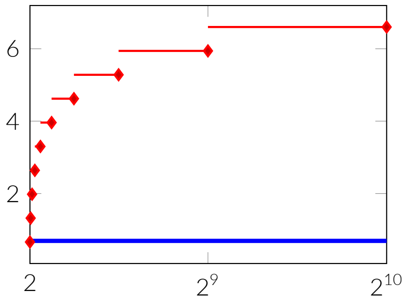
- Chained CmPKE (**upload**) with {Bilbo640, SIKEp434}
- Chained CmPKE (**download**) with {Bilbo640, SIKEp434}
- TreeKEM (**upload and download**) with {Frodo640, SIKEp434}

Chained CmPKE vs TreeKEM (total normalised by N)

Normalised cost of a commit message in KiB as a function of the group size.



(a) Bilbo640 vs. Frodo640

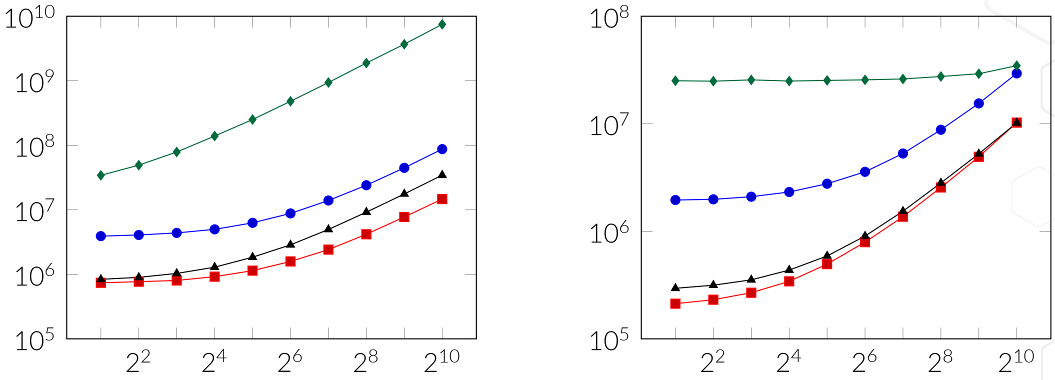


(b) SIKEp434 vs. SIKEp434

Chained CmPKE with {Bilbo640, SIKEp434}

TreeKEM with {Frodo640, SIKEp434}

Computational cost of a commit message



(a) Commit (sender side)   (b) Process (receiver side)

Running time of some procedures as a function of the group size, for Ilum512 (■), LPRime757 (▲), Bilbo640 (●), SIKEp434 (◆). Logarithmic scales. Timings obtained on an Apple M1 @3.2 GHz.

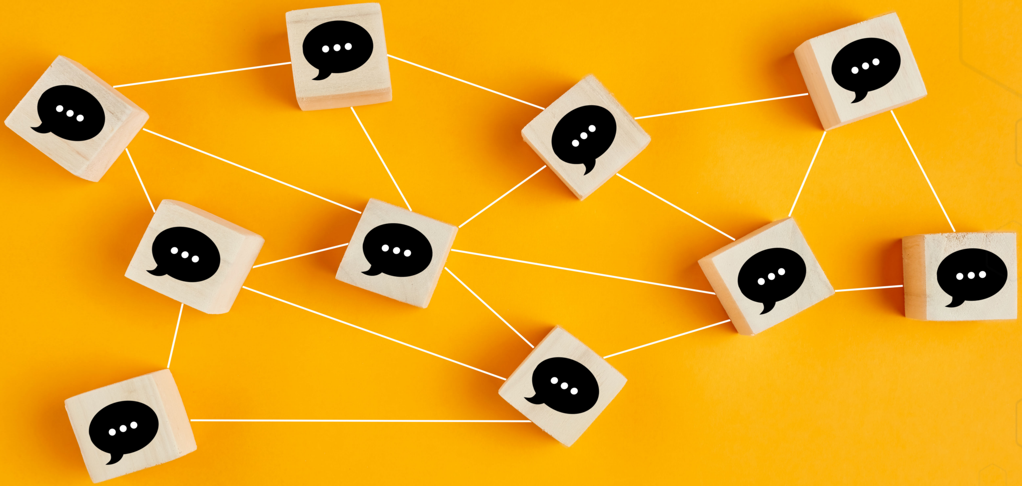
Conclusion

We proposed *Chained CmPKE*, a CGKA that is:

- Very fast
- More compact than TreeKEM: $O(N)$ instead of $\Omega(N \log N)$
- Simpler than TreeKEM
- Satisfying the same security notions (see paper)

As well as techniques that might be of independent interest:

1. *Committing mPKEs*
2. More efficient lattice-based mPKEs



Questions?

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