Analysis and Improvements of the Sender Keys Protocol for Group Messaging

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October 21, 2022

RECSI 2022, Santander

European Research Council
Established by the European Commission

WhatsUpp with Sender Keys?

- **Messaging protocols** used by billions daily.
  Commercial solutions claim **security** + **end-to-end encryption**.
- Formal protocol analysis is important. Becomes harder in **groups**.

- **Signal**: Extends Double Ratchet. *Slow; not completely understood.*
- **Telegram**: No end-to-end encryption. *Not ideal.*
- **MLS**: Lots of theoretical analysis. *Secure and efficient but complex.*
- **WhatsApp**: Sender Keys. *No protocol analysis so far.*

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We study the **Sender Keys Protocol** used in WhatsApp groups.

Protocol extracted from WhatsApp's whitepaper + Signal code.

- **Formalization**: Cryptographic primitive, security modelling.
- **Security Analysis**: Issues with concurrency, group membership, recovery from compromise, authentication...
- **Improvements**: Patching our attacks, key updates, securing membership.

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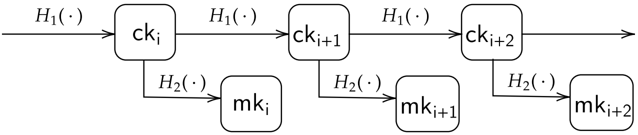
Messaging and Sender Keys

Sender Keys: Main Protocol

- Every ID $\in \boldsymbol{G}$ owns a symmetric *chain key* $\texttt{ck}_{\text{ID}}$ shared with all members.
- **Sending**: ID encrypts m using a *message key* $\texttt{mk}$ that is deterministically derived from $\texttt{ck}_{\text{ID}}$.



- **Receiving**, members derive $\texttt{mk}$ from $\texttt{ck}_{\text{ID}}$ to decrypt and read m.
- Forward security provided by a fresh $\texttt{mk}$ every time – *symmetric ratchet* using hash functions.
- Additionally, senders *sign application messages*.

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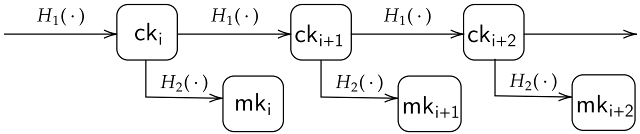

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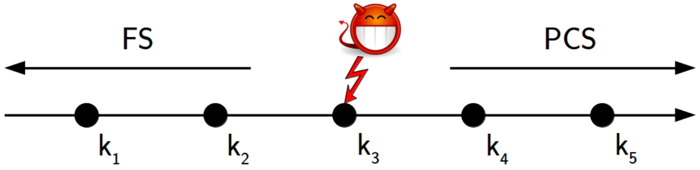
What is expected from Sender Keys?

- Correctness, authentication.
- **Forward Security (FS)** - *past* messages safe.
- **Post-Compromise Security (PCS)** - *self-healing*



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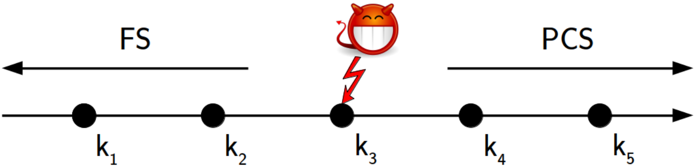

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Sender Keys: Message Exchange

$$\mathbf{A} : (\mathsf{ck}_A^i, \mathsf{ssk}_A, \mathsf{spk}_A, \mathsf{ck}_B^j, \mathsf{spk}_B)$$

$$\mathbf{B} : (\mathsf{ck}_B^j, \mathsf{ssk}_B, \mathsf{spk}_B, \mathsf{ck}_A^i, \mathsf{spk}_A)$$

A sends m_i

$$\mathsf{mk}_A^i \leftarrow H_1(\mathsf{ck}_A^i)$$

$$c_i \xleftarrow{\$} \mathsf{Enc}(\mathsf{mk}_A^i, m_i) \qquad \xrightarrow{(c_i, i, A, \sigma_i)} \qquad \textbf{req } \mathsf{Ver}(\mathsf{spk}_A, \sigma_i) = 1$$

$$\mathsf{ck}_A^{i+1} \leftarrow H_2(\mathsf{ck}_A^i) \qquad\qquad \mathsf{mk}_A^i \leftarrow H_1(\mathsf{ck}_A^i)$$

$$\sigma_i \xleftarrow{\$} \mathsf{Sig}(\mathsf{ssk}_A, (c_i, i, A)) \qquad\qquad m_i \leftarrow \mathsf{Dec}(\mathsf{mk}_A^i, c_i)$$

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Sender Keys: Key Agreement & Membership

Sender Keys relies on *existing authenticated and confidential two-party channels (2pc)* between all users (strong assumption!).

- If ID joins $\boldsymbol{G}$, it generates new `ck` and `spk` and sends it to everyone in $\boldsymbol{G}$ via 2pc. This is done the first time ID speaks.
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Security

Primitive and Security Model

A Group Messenger (GM) includes:

- $(C, \gamma') \xleftarrow{\$} Send(m, \gamma)$
- $(m, e, i, \gamma') \leftarrow Recv(C, \gamma)$
- $(T, \gamma') \xleftarrow{\$} Exec(\texttt{cmd}, \boldsymbol{IDs}, \gamma)$
- $\gamma' \leftarrow Proc(T, \gamma)$

We introduce a *message indistinguishability* security game.

Active, adaptive $\mathcal{A}$ that can *forge and inject messages*.

We disallow *'trivial attacks'*: challenge and inject using exposed keys.

Game Oracles:

- Create(ID, ***IDs***)
- Challenge(ID, m_0, m_1)
- Send(ID, m)
- Receive(ID, ID′, C)
- Add(ID, ID′)
- Remove(ID, ID′)
- Update(ID)
- Deliver(ID, T)
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- ExpMK(ID, e, i)
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Two Attacks

Assuming ideal two-party channels, we still find some issues:

Control Messages

These are *not authenticated* and can be forged without any exposure.

Server can add/remove parties on behalf of other users. *Insecure membership* [RMS18, ACDJ22, BCV22].

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Only 'removes' allow for PCS in Sender Keys. Can we do updates?

- **Naive approach:** ID sends a fresh ck to all users [CHK21]. Problem: only messages encrypted under ck recover security.
- **Alternative idea:** ID sends *fresh randomness* r to all users; $\mathtt{ck}_{\mathsf{ID}'} \leftarrow H(\mathtt{ck}_{\mathsf{ID}'} || r)$ is computed for all ID′s.

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Realistic two-party Channels

If ID is removed, assuming secure 2pc:

- Members process removal & erase keys - free from every exposure!
- Generate and send fresh keys over secure 2pc.

Looks great! Keys sent safely, key material erased, exposures resolved. PCS is achieved.

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Final Remarks

Conclusions and Future Work

Takeaways:

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- *Improvements*: Update options (even if strong PCS impossible), efficiency, security.

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So, WhatsUpp with Sender Keys?

¡Gracias!

Slides (and more!) at:
`davidbalbas.github.io`

Appendix: Single- vs multi-key

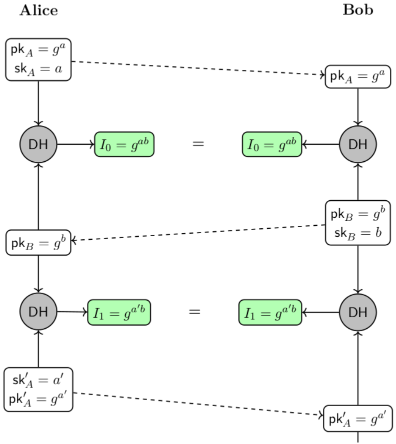
Each ID has a different `ck`, so the state has $O(n)$ secret material at all times. We observe:

- Security comparable if all users have *the same chain key* (single-key group). Everyone knows all secret material except signature keys.
- Different chain keys are essentially useful for *concurrency*.
- One could envision trade-offs depending on how active users are. A central server could be employed to help.

For example, in MLS a common group secret is agreed (with possible PCS). Then, $O(n)$ application keys are derived from it to improve concurrency.

PCS after users leave

In the Double Ratchet, we require a full roundtrip for state exposure recovery (hence for PCS).



An attack vector

1. ID is *exposed*. Then $\mathcal{A}$ knows its DR keys with everyone.
2. Someone leaves the group. Users erase their old keys.
3. ID' sends a new sender key to ID via their DR.
4. $\mathcal{A}$ can read the key despite ID's updated pk.

This raises **open questions:**

- Can we *improve* this mechanism?
- Do we need a fresh, *interactive* key exchange?
- Can PCS be recovered at all (just by sending keys)?
- What is the *exact* security we get?

Current approach: simplified modelling of underlying channels

Security in ideal model

We disallow 'trivial attacks' when party ID is exposed:

- Cannot inject (via `Receive`) previous messages and future until ID is removed;
- Cannot `Challenge` using keys learnt from ID until removal of ID′/update.
- Game only delivers honestly generated control messages.

Then, we can prove security assuming ideal 2pc. Some remarks:

- Message keys $\mathtt{mk}_i$ can be exposed independently, never affecting other keys.
- *Assuming perfect 2pc*, users recover from exposure after a removal.