Impact Tracing: Identifying the Culprit of Misinformation in Encrypted Messaging Systems

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CHONGQING UNIVERSITY

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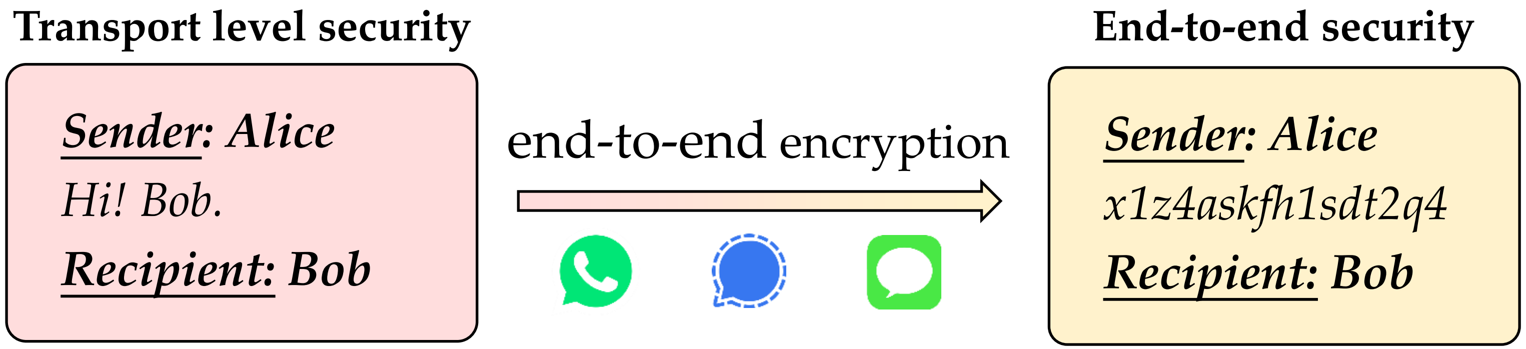
Content Moderation for EEMSs

End-to-end encrypted messaging systems (EEMS):

Only the END users can read the messages.



Transport level security

Sender*: *Alice

Hi! Bob.

Recipient*: *Bob

end-to-end encryption

End-to-end security

Sender*: *Alice

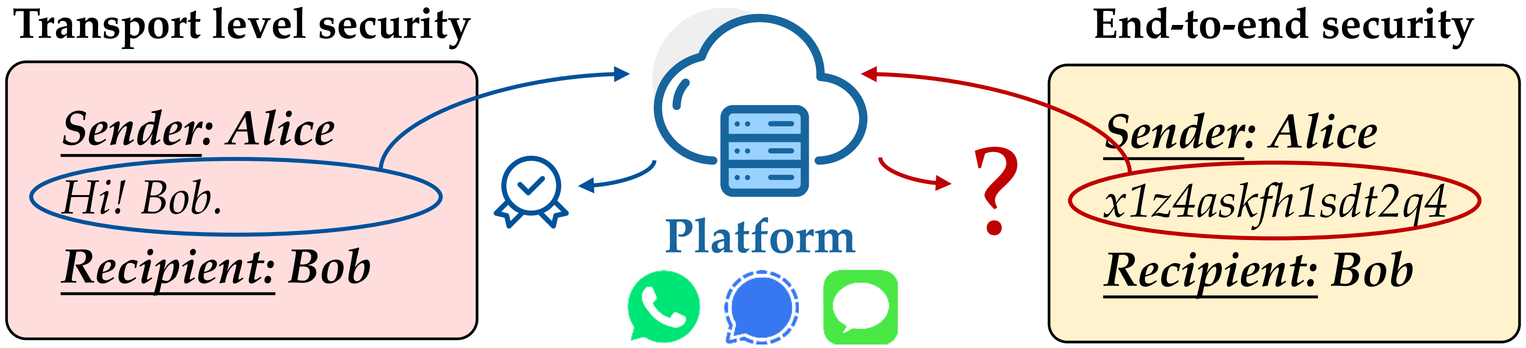
x1z4askfh1sdt2q4

Recipient*: *Bob

Content Moderation for EEMSs

End-to-end encrypted messaging systems (EEMS):

Only the END users can read the messages.



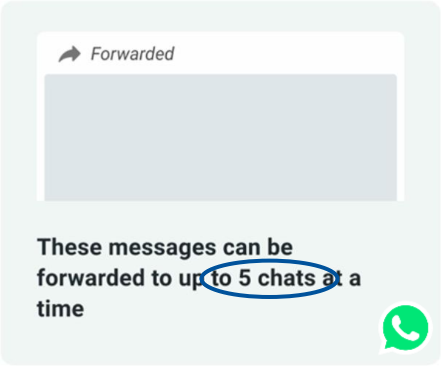
Problematic messages proliferates in EEMSs.

End-to-end encryption obstructs content moderation :(

[TAB+21,S&P] SoK: Hate, Harassment, and the Changing Landscape of Online Abuse

Message Forwarding & Tracing

Misinformation propagate rapidly through forwarding.



These messages can be forwarded to up to 5 chats at a time

Message Forwarding & Tracing

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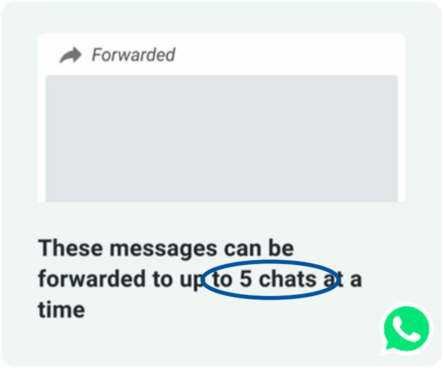

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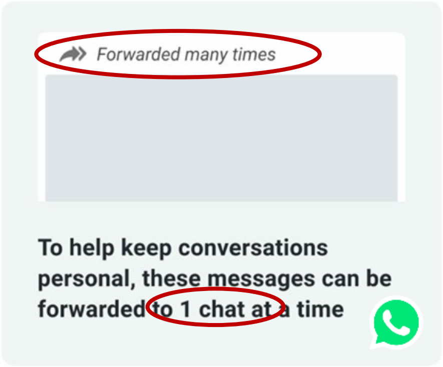
Forward limit



To help keep conversations personal, these messages can be forwarded to 1 chat at a time

Message Forwarding & Tracing

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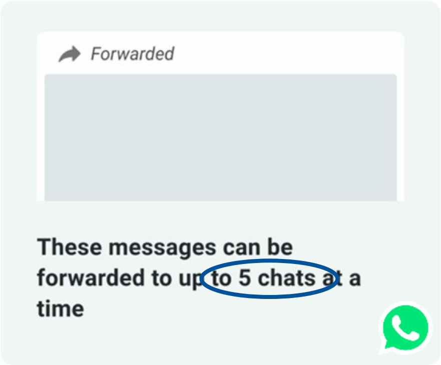
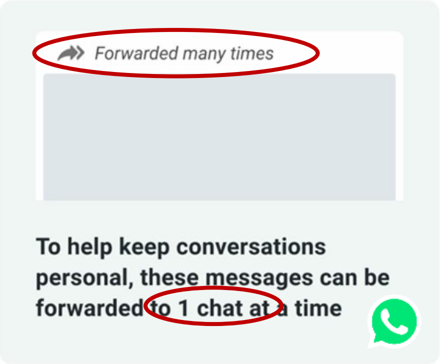


Forwarded

These messages can be forwarded to up to 5 chats at a time

Forward limit

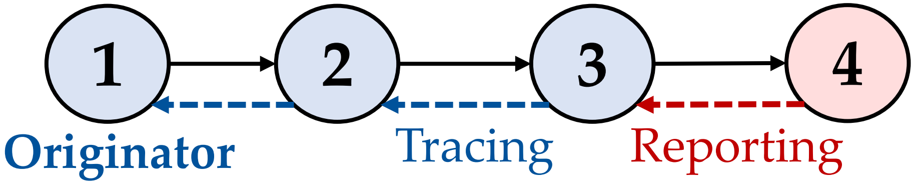


Forwarded many times

To help keep conversations personal, these messages can be forwarded to 1 chat at a time

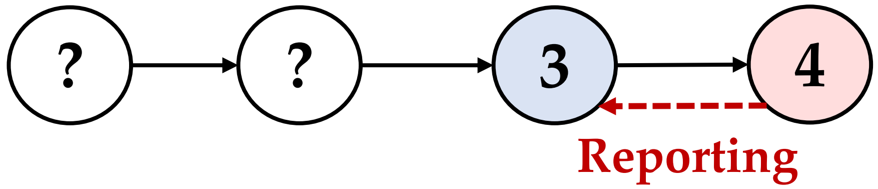
Traceability enables tracing after user reporting.

- The platform can disclose the dissemination path.



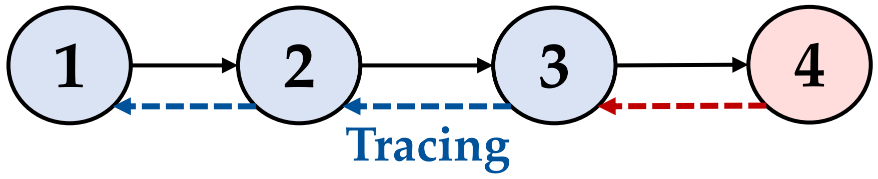
https://faq.whatsapp.com/1053543185312573/?helpref=uf_share

Tracing Policies



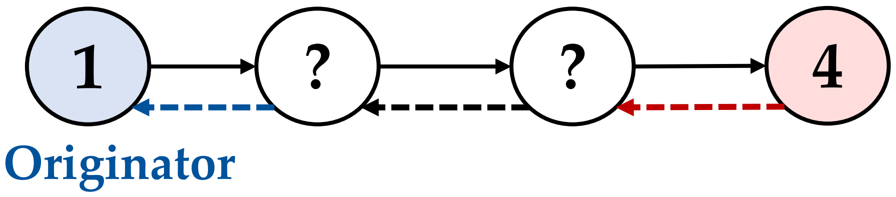
Message Franking

[Facebook17,RWC], [GLR17,CRYPTO], [TGL+19,CRYPTO], [GPE25,NDSS], etc.



Message Traceback

[TMR19,CCS], [KTW22,ESORICS]



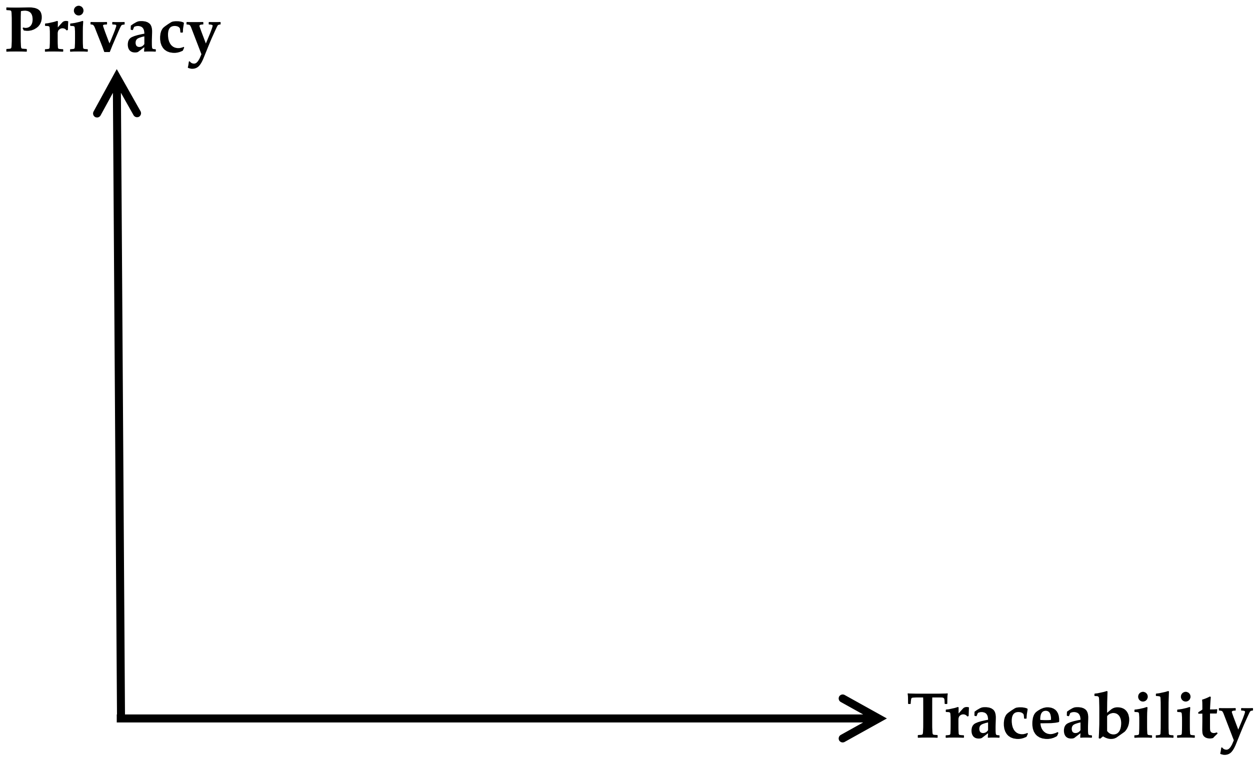
Source Tracing

[PEB21,CCS], [IAV22,Usenix Sec.], [LRTY22,NDSS], [BGJP23,EUROCRYPT], [BE24,PETS], etc.

Which part of the dissemination path is tracked during tracing?

Traceability vs. Privacy

- **Traceability:** Reveal the culprits of spreading misinformation.
- **Privacy:** Reveal nothing about forwarding path.



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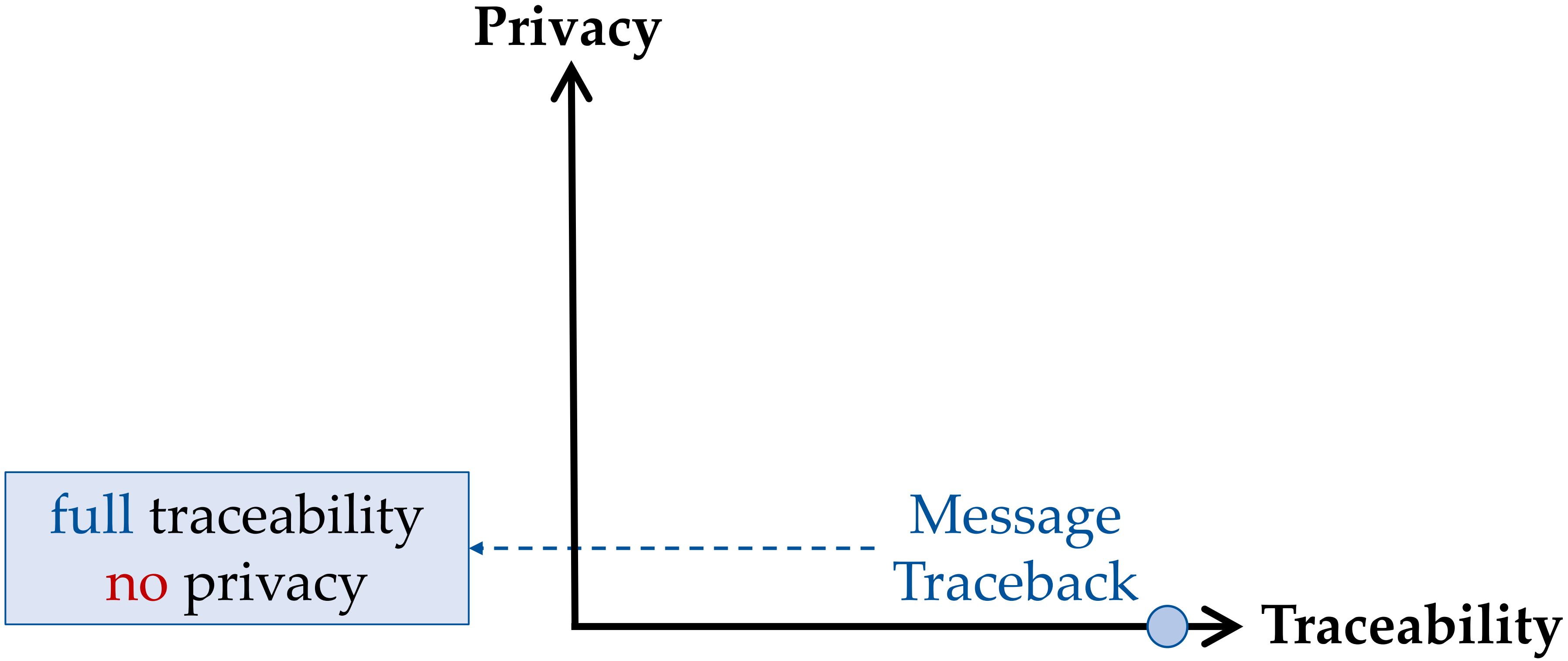

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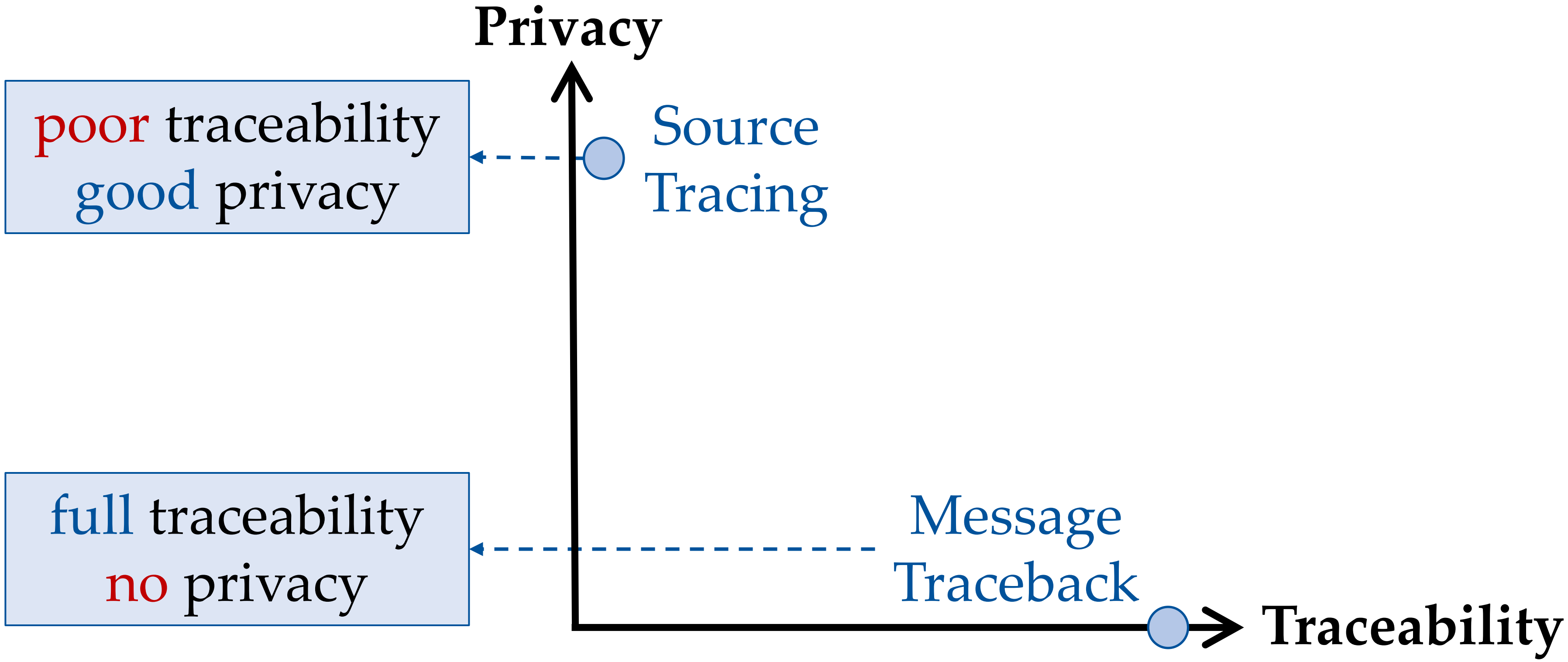

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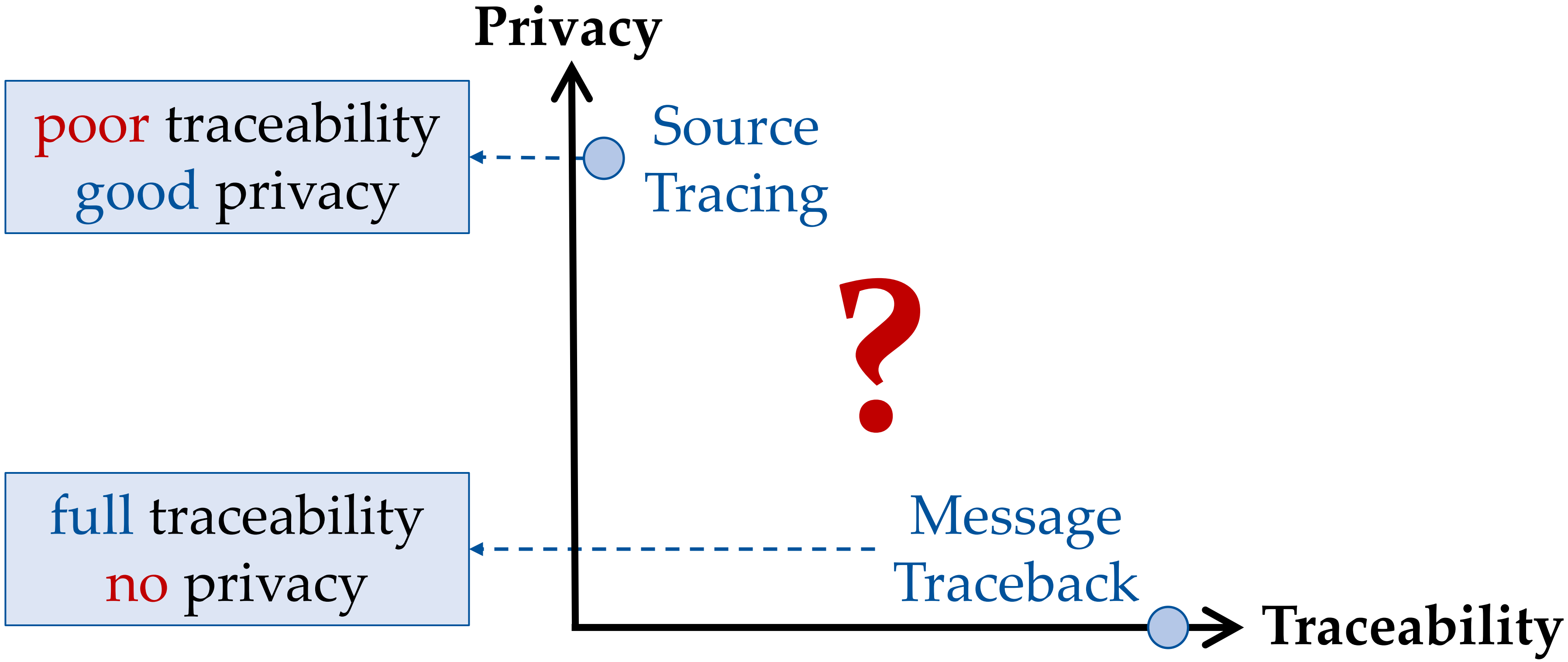
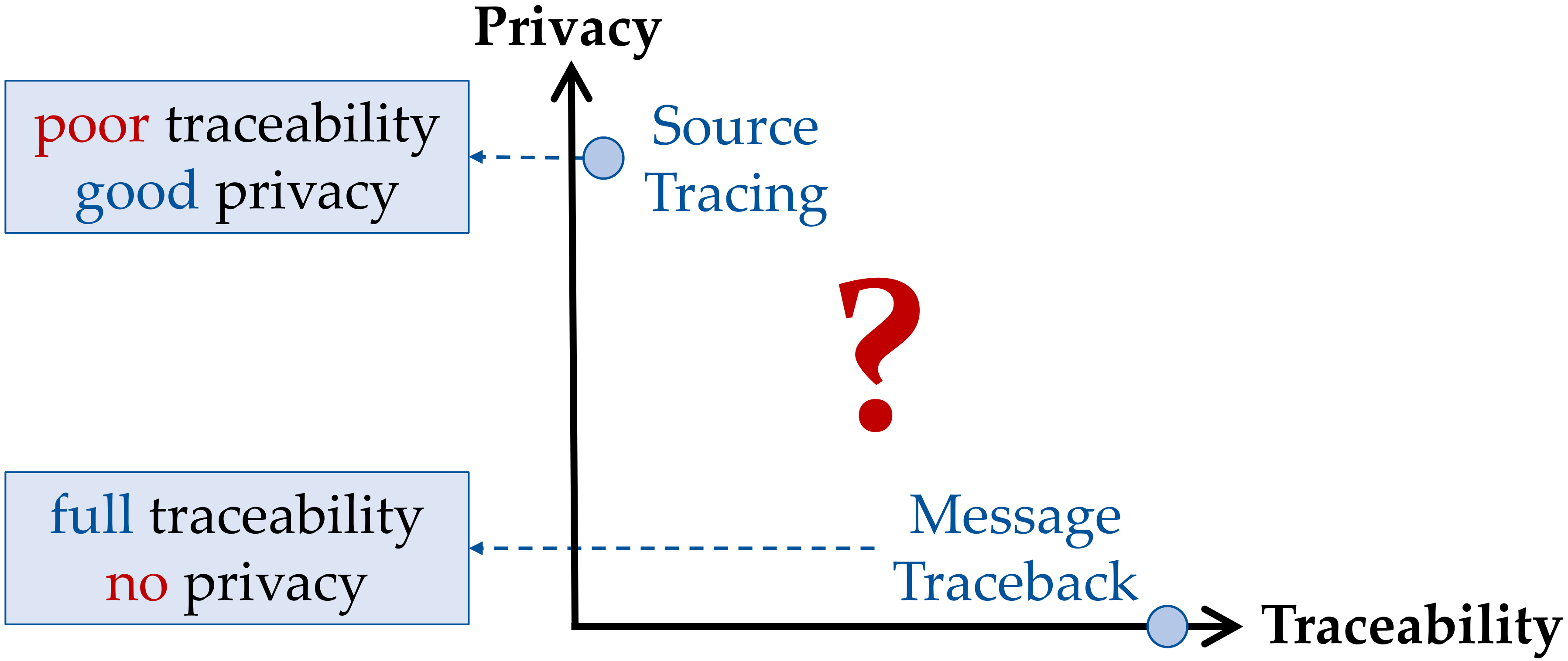


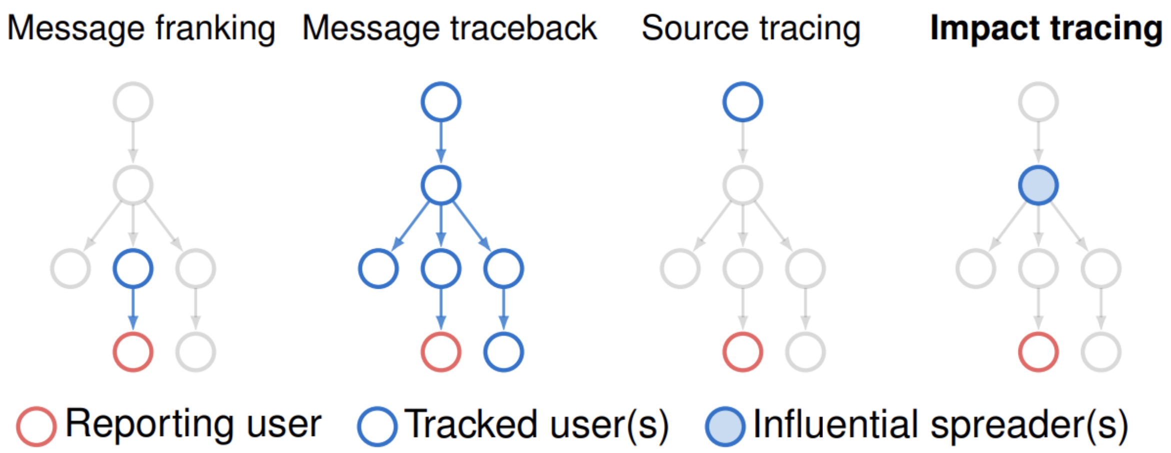
Traceability vs. Privacy

Is there a tracing policy that balances traceability and privacy, but also provides practical values to EEMSs?



Our Solution: Impact Tracing!

A small group of users (called influential spreaders) *significantly* contribute to spreading misinformation.



Traceability: The platform *can* identify influential spreaders.

Privacy: The platform *cannot* uncover non-influential users.

[CCDT21,Report] The Disinformation Dozen: Why Platforms must Act on Twelve Leading Online Anti-Vaxxers

The Design: Enabling Reporting

Sender

Platform

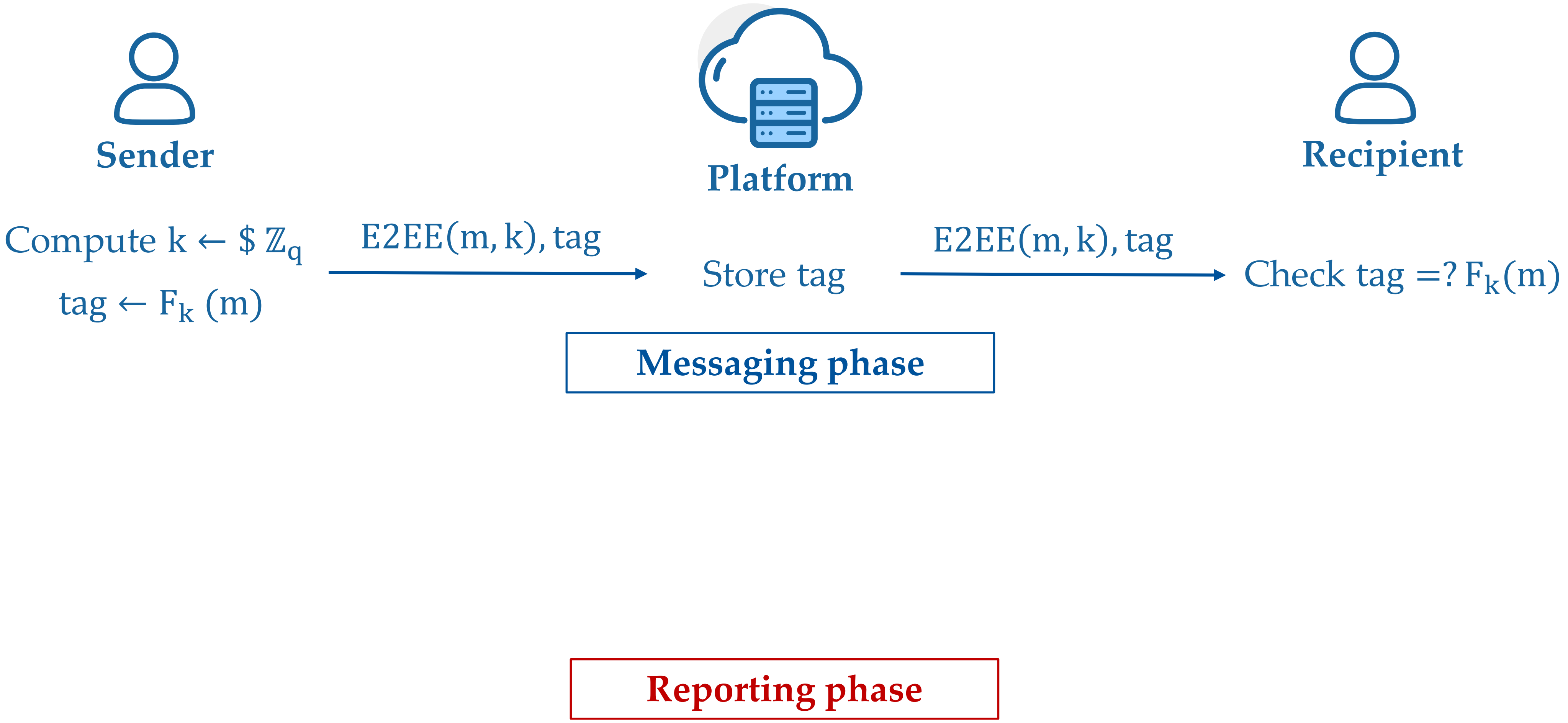
Recipient

Messaging phase

Reporting phase

[Facebook17,RWC] Challenges of E2E Encryption in Facebook Messenger

The Design: Enabling Reporting



Sender

Platform

Recipient

Compute $k \leftarrow \$\ \mathbb{Z}_q$

tag $\leftarrow \mathrm{F}_k\ (m)$

$\xrightarrow{\mathrm{E2EE}(m, k), \mathrm{tag}}$

Store tag

$\xrightarrow{\mathrm{E2EE}(m, k), \mathrm{tag}}$

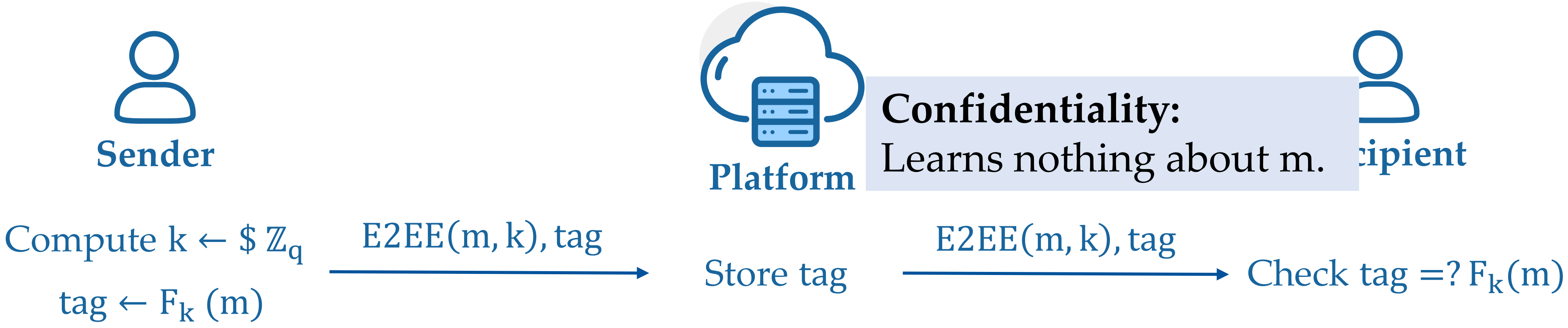
Check tag $=?\ \mathrm{F}_k(m)$

Messaging phase

Reporting phase

[Facebook17,RWC] Challenges of E2E Encryption in Facebook Messenger

The Design: Enabling Reporting



Confidentiality:
Learns nothing about m.

Compute $k \leftarrow \$ \, \mathbb{Z}_q$

$\text{tag} \leftarrow F_k \, (m)$

$\xrightarrow{\text{E2EE}(m, k), \text{tag}}$

Store tag

$\xrightarrow{\text{E2EE}(m, k), \text{tag}}$

Check $\text{tag} =? F_k(m)$

Messaging phase

Reporting phase

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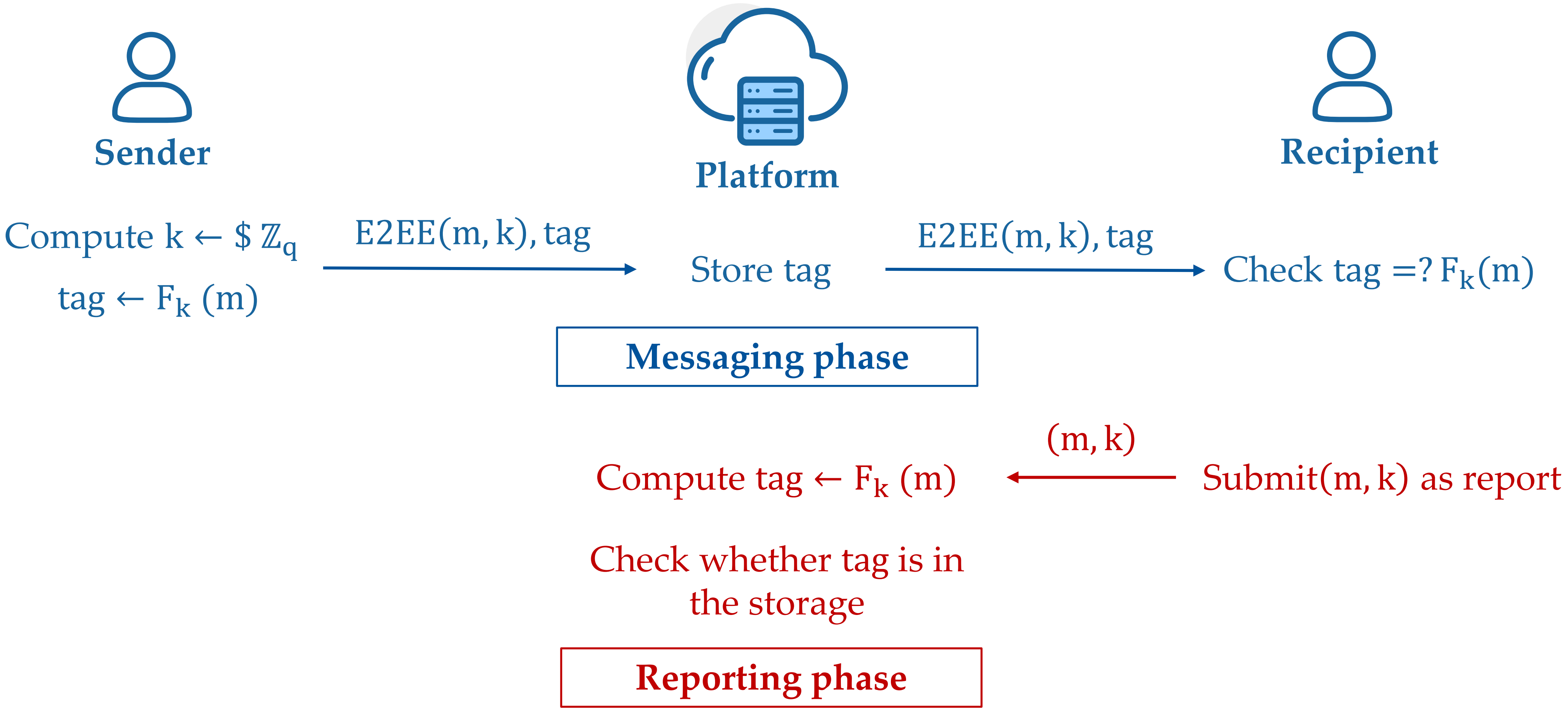

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Recipient

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$\text{E2EE}(m, k), \text{tag}$

Store tag

$\text{E2EE}(m, k), \text{tag}$

Check tag $=? \, F_k(m)$

Messaging phase

(m, k)

Compute $\text{tag} \leftarrow F_k\,(m)$

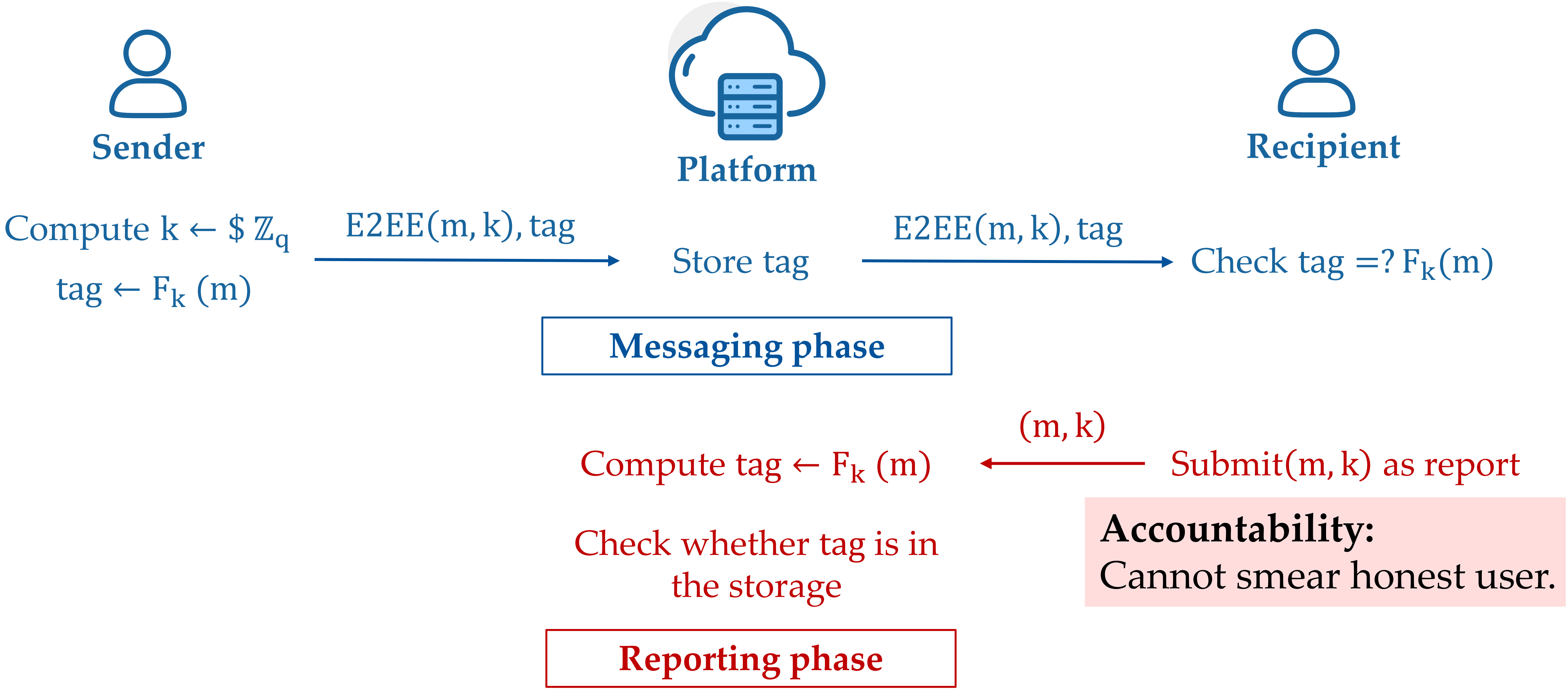
Submit(m, k) as report

Check whether tag is in the storage

Reporting phase

[Facebook17,RWC] Challenges of E2E Encryption in Facebook Messenger

The Design: Enabling Reporting



Sender

Platform

Recipient

Compute $k \leftarrow \$\ \mathbb{Z}_q$

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$\text{E2EE}(m, k), \text{tag}$

Store tag

$\text{E2EE}(m, k), \text{tag}$

Check tag $=?\ F_k(m)$

Messaging phase

(m, k)

Compute tag $\leftarrow F_k\ (m)$

Submit(m, k) as report

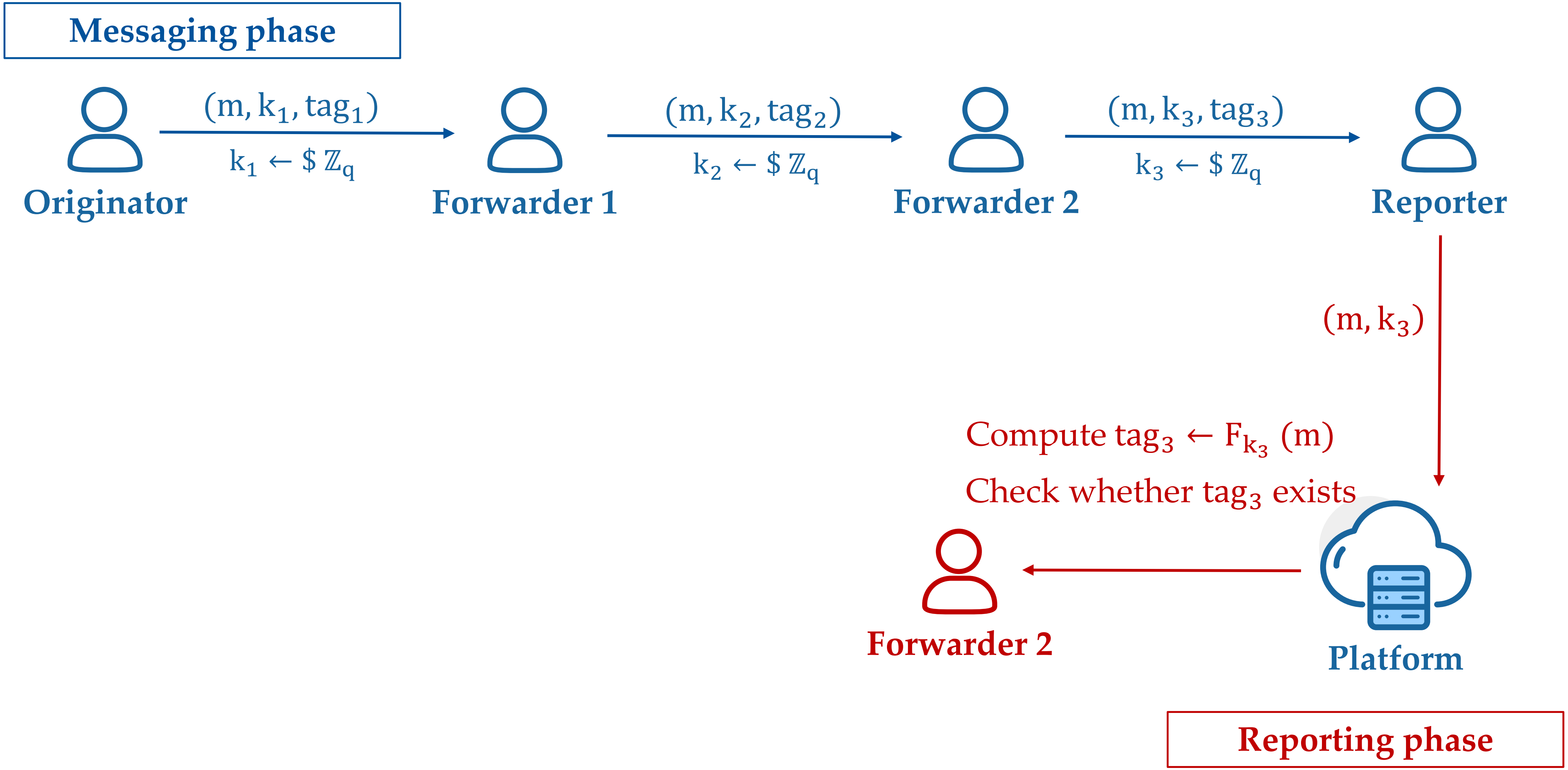
Check whether tag is in the storage

Accountability:
Cannot smear honest user.

Reporting phase

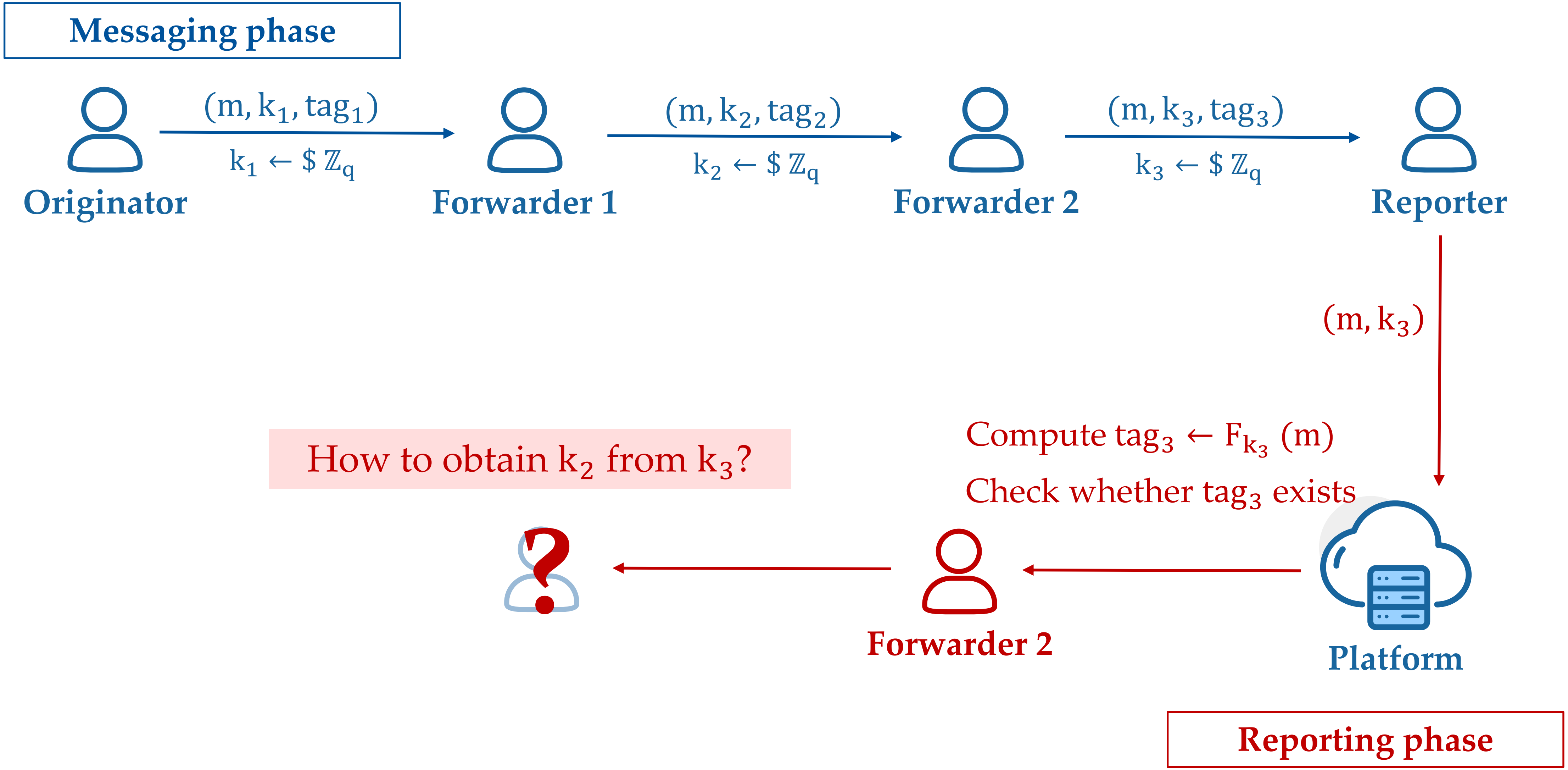
[Facebook17,RWC] Challenges of E2E Encryption in Facebook Messenger

The Design: Enabling Reporting



Messaging phase
(m, k_1, tag_1)
$k_1 \leftarrow \$ \mathbb{Z}_q$
Originator
(m, k_2, tag_2)
$k_2 \leftarrow \$ \mathbb{Z}_q$
Forwarder 1
(m, k_3, tag_3)
$k_3 \leftarrow \$ \mathbb{Z}_q$
Forwarder 2
Reporter
(m, k_3)
Compute $tag_3 \leftarrow F_{k_3}(m)$
Check whether tag_3 exists
Forwarder 2
Platform
Reporting phase

The Design: Enabling Reporting



Messaging phase

Originator

(m, k_1, tag_1)

$k_1 \leftarrow \$ \, \mathbb{Z}_q$

Forwarder 1

(m, k_2, tag_2)

$k_2 \leftarrow \$ \, \mathbb{Z}_q$

Forwarder 2

(m, k_3, tag_3)

$k_3 \leftarrow \$ \, \mathbb{Z}_q$

Reporter

(m, k_3)

Compute $tag_3 \leftarrow F_{k_3}(m)$

Check whether tag_3 exists

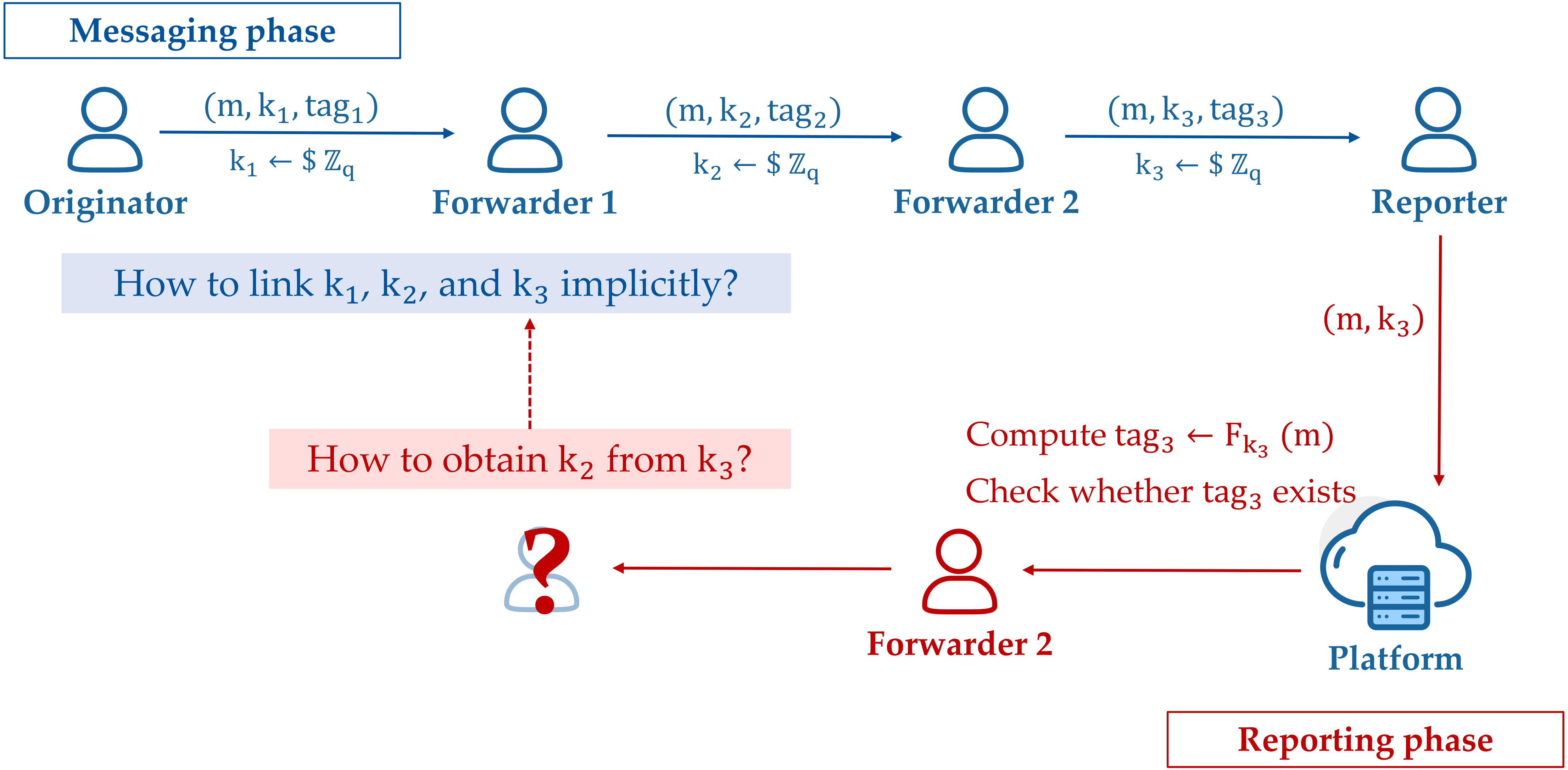
Platform

Forwarder 2

How to obtain k_2 from k_3?

Reporting phase

The Design: Enabling Reporting



Messaging phase

How to link k_1, k_2, and k_3 implicitly?

How to obtain k_2 from k_3?

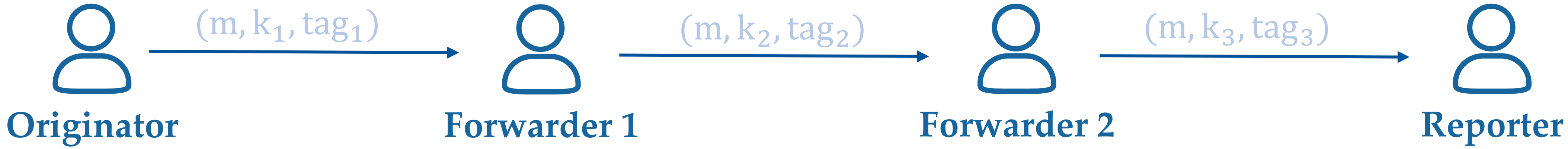
Compute $tag_3 \leftarrow F_{k_3}(m)$

Check whether tag_3 exists

Reporting phase

The Design: Reporting then Tracing

Messaging phase



(m, k_1, tag_1)

(m, k_2, tag_2)

(m, k_3, tag_3)

Originator

Forwarder 1

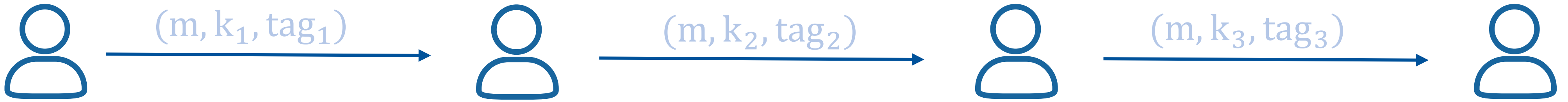
Forwarder 2

Reporter

The Design: Reporting then Tracing

Messaging phase

ik: Users' secret identity key; **U:** Users' public identity; **Enc:** Block cipher



(m, k_1, tag_1) (m, k_2, tag_2) (m, k_3, tag_3)

Originator

$tk_{01} \leftarrow H(ik_0 || U_1)$

$k_1 \leftarrow Enc_{tk_{01}}(k_0)$

$k_0 \leftarrow \$ \, \mathbb{Z}_q$

Forwarder 1

$tk_{12} \leftarrow H(ik_1 || U_2)$

$k_2 \leftarrow Enc_{tk_{12}}(k_1)$

Forwarder 2

$tk_{23} \leftarrow H(ik_2 || U_3)$

$k_3 \leftarrow Enc_{tk_{23}}(k_2)$

Reporter

The Design: Reporting then Tracing

Messaging phase

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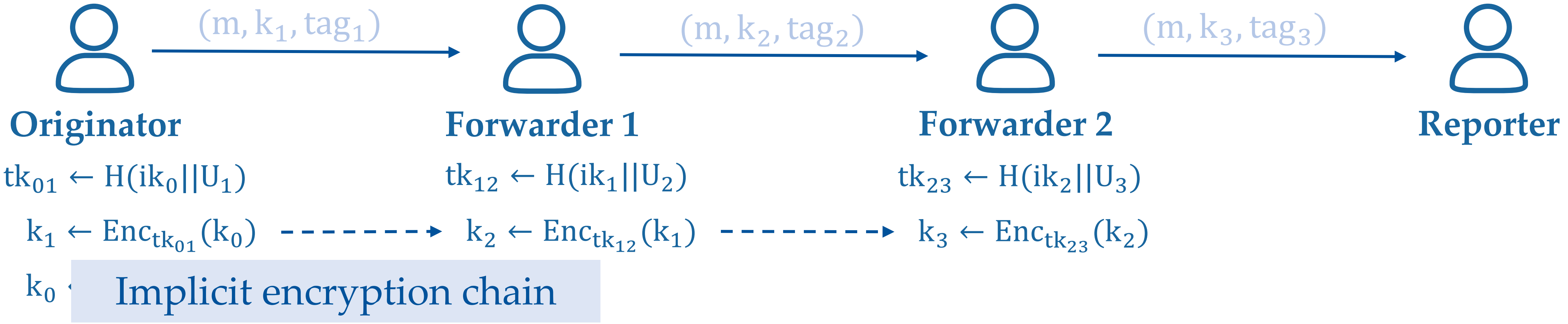


$(\mathrm{m}, \mathrm{k}_1, \mathrm{tag}_1)$

$(\mathrm{m}, \mathrm{k}_2, \mathrm{tag}_2)$

$(\mathrm{m}, \mathrm{k}_3, \mathrm{tag}_3)$

Originator

Forwarder 1

Forwarder 2

Reporter

$\mathrm{tk}_{01} \leftarrow \mathrm{H}(\mathrm{ik}_0 || \mathrm{U}_1)$

$\mathrm{k}_1 \leftarrow \mathrm{Enc}_{\mathrm{tk}_{01}}(\mathrm{k}_0)$

k_0

$\mathrm{tk}_{12} \leftarrow \mathrm{H}(\mathrm{ik}_1 || \mathrm{U}_2)$

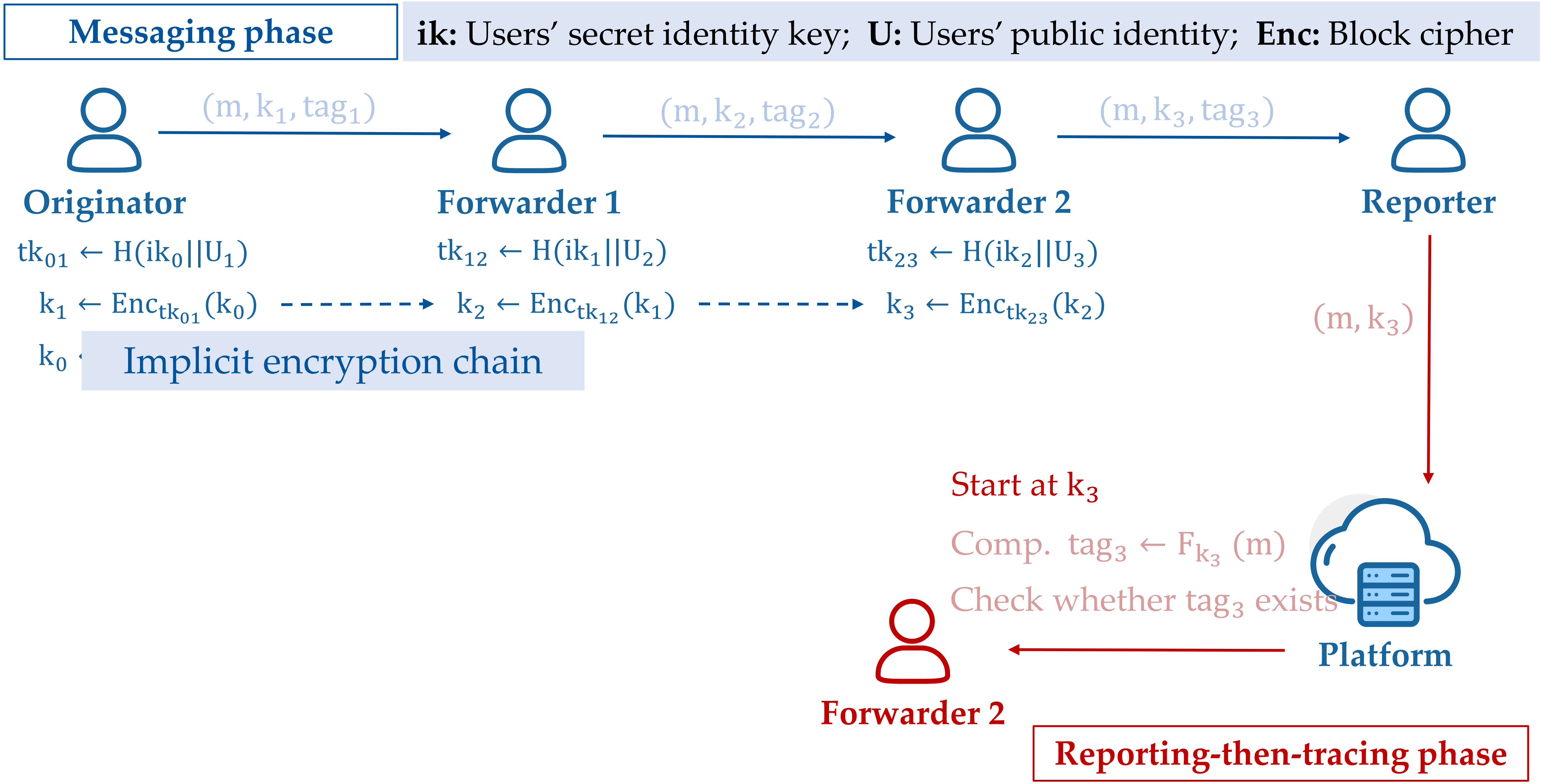
$\mathrm{k}_2 \leftarrow \mathrm{Enc}_{\mathrm{tk}_{12}}(\mathrm{k}_1)$

$\mathrm{tk}_{23} \leftarrow \mathrm{H}(\mathrm{ik}_2 || \mathrm{U}_3)$

$\mathrm{k}_3 \leftarrow \mathrm{Enc}_{\mathrm{tk}_{23}}(\mathrm{k}_2)$

Implicit encryption chain

The Design: Reporting then Tracing



Messaging phase

ik: Users' secret identity key; **U:** Users' public identity; **Enc:** Block cipher

(m, k_1, tag_1)

(m, k_2, tag_2)

(m, k_3, tag_3)

Originator

$tk_{01} \leftarrow H(ik_0 || U_1)$

$k_1 \leftarrow Enc_{tk_{01}}(k_0)$

k_0

Implicit encryption chain

Forwarder 1

$tk_{12} \leftarrow H(ik_1 || U_2)$

$k_2 \leftarrow Enc_{tk_{12}}(k_1)$

Forwarder 2

$tk_{23} \leftarrow H(ik_2 || U_3)$

$k_3 \leftarrow Enc_{tk_{23}}(k_2)$

Reporter

(m, k_3)

Start at k_3

Comp. $tag_3 \leftarrow F_{k_3}(m)$

Check whether tag_3 exists

Platform

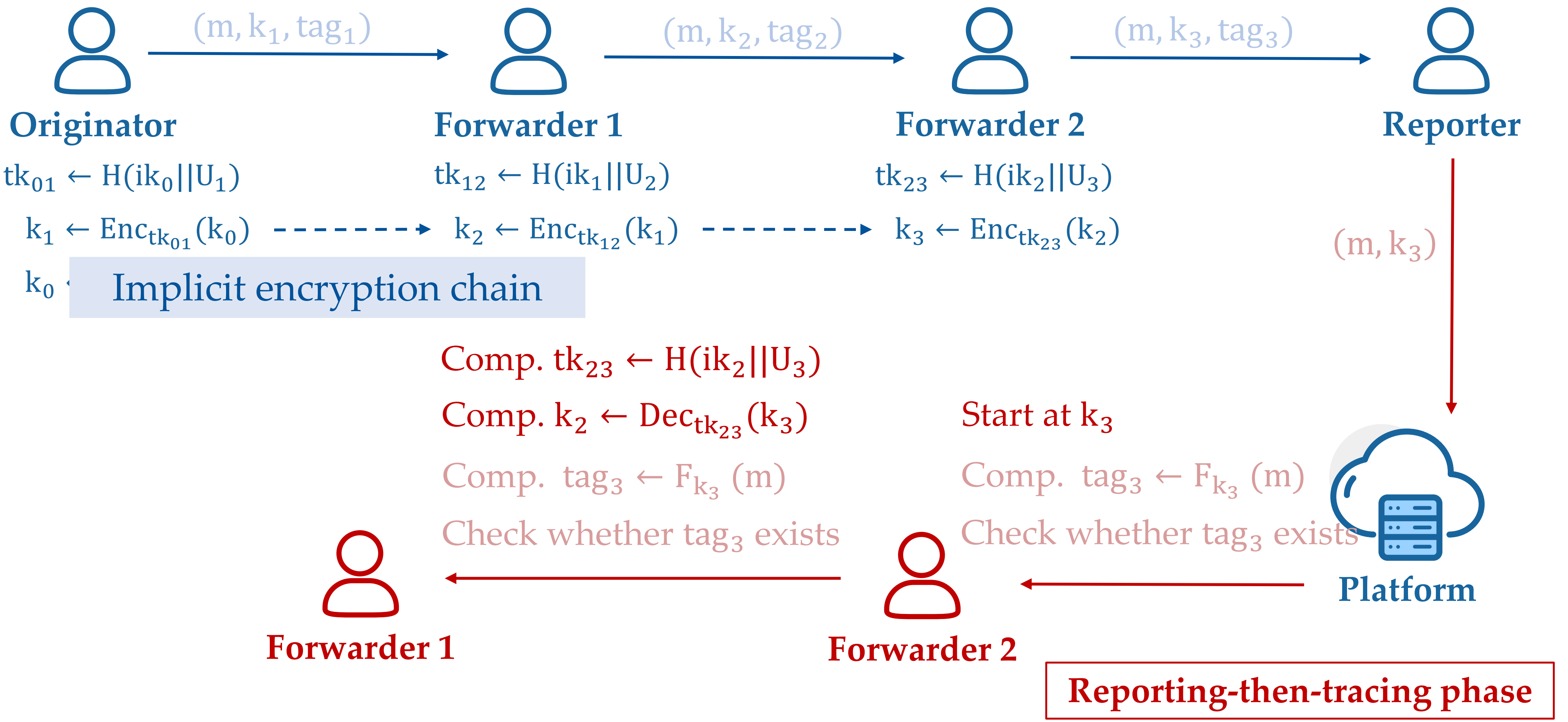
Forwarder 2

Reporting-then-tracing phase

The Design: Reporting then Tracing

Messaging phase

ik: Users' secret identity key; **U:** Users' public identity; **Enc:** Block cipher



(m, k_1, tag_1)

(m, k_2, tag_2)

(m, k_3, tag_3)

Originator

$tk_{01} \leftarrow H(ik_0||U_1)$

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k_0

Forwarder 1

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Reporter

Implicit encryption chain

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Check whether tag_3 exists

Platform

Comp. $tk_{23} \leftarrow H(ik_2||U_3)$

Comp. $k_2 \leftarrow Dec_{tk_{23}}(k_3)$

Comp. $tag_3 \leftarrow F_{k_3}(m)$

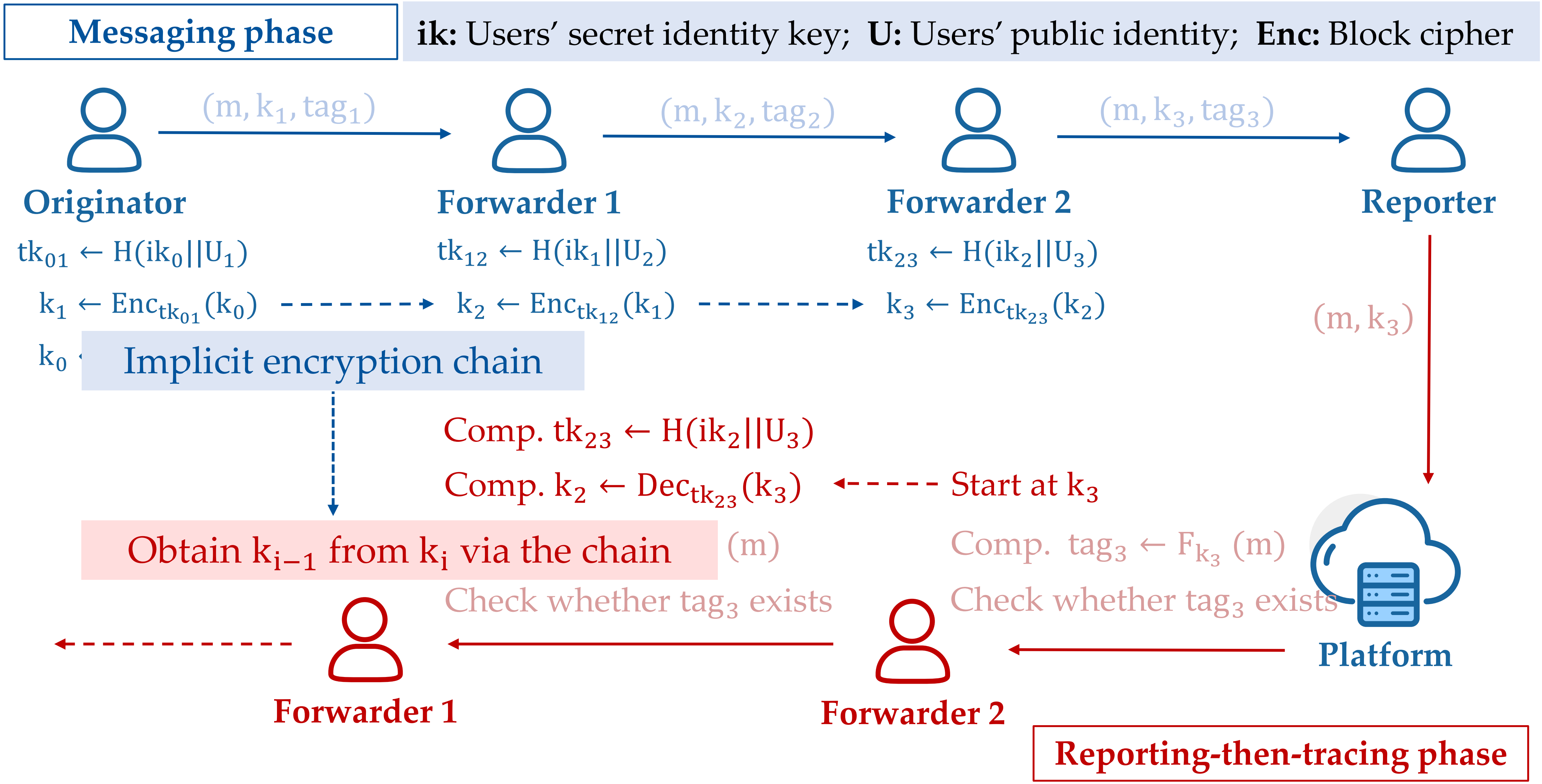
Check whether tag_3 exists

Forwarder 2

Forwarder 1

Reporting-then-tracing phase

The Design: Reporting then Tracing



Messaging phase

ik: Users' secret identity key; **U:** Users' public identity; **Enc:** Block cipher

Originator $\xrightarrow{(m, k_1, tag_1)}$ **Forwarder 1** $\xrightarrow{(m, k_2, tag_2)}$ **Forwarder 2** $\xrightarrow{(m, k_3, tag_3)}$ **Reporter**

Originator:

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$k_0 \leftarrow$

Forwarder 1:

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Forwarder 2:

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$k_3 \leftarrow Enc_{tk_{23}}(k_2)$

Implicit encryption chain

Reporter → Platform: (m, k_3)

Start at k_3

Comp. $tk_{23} \leftarrow H(ik_2 || U_3)$

Comp. $k_2 \leftarrow Dec_{tk_{23}}(k_3)$

Obtain k_{i-1} from k_i via the chain

Platform → Forwarder 2: (m)

Comp. $tag_3 \leftarrow F_{k_3}(m)$

Check whether tag_3 exists

Forwarder 2 → Forwarder 1: (m)

Check whether tag_3 exists

Platform

Forwarder 2

Forwarder 1

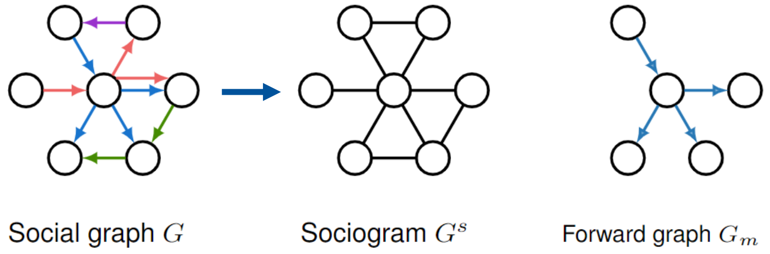
Reporting-then-tracing phase

The Design: Reporting then Tracing

Messaging phase:

- Users forward messages.

- Platform collects sociogram & stores tags.



The Design: Reporting then Tracing

Messaging phase:

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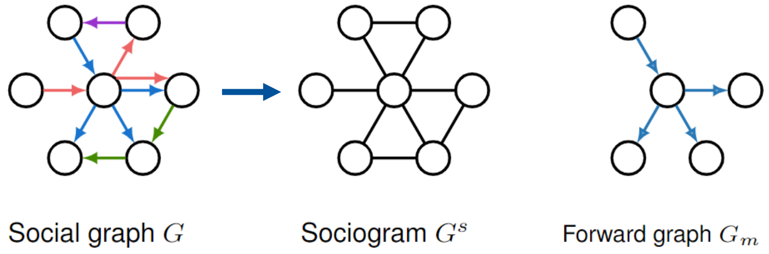
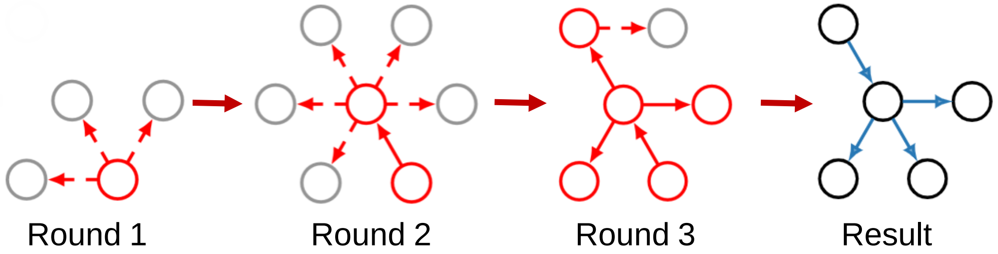


Reporting-then-Tracing phase:

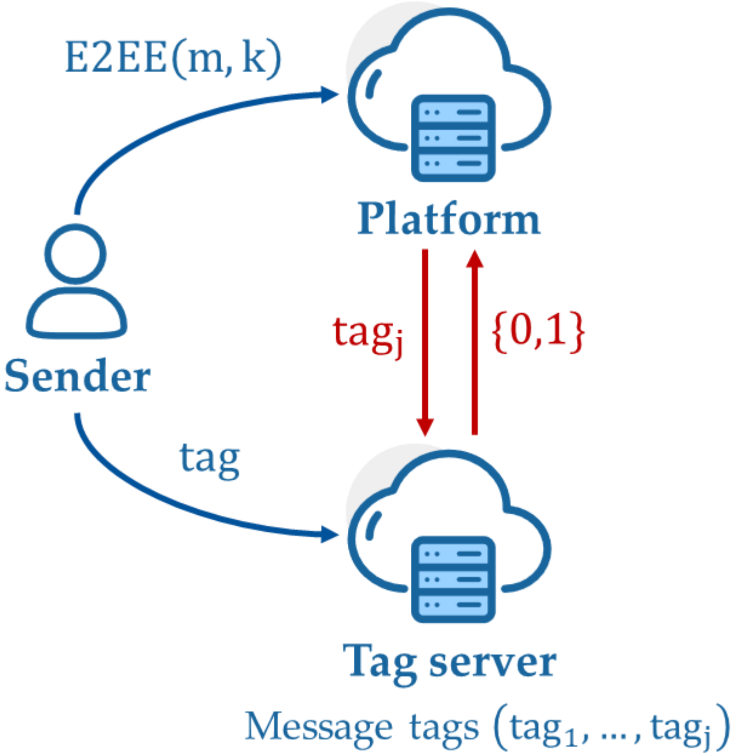
1) Compute tag key and tag.
2) Check the existence of the tag.
3) Start next round at existed vertices.



The Design: Noising the Traceback

Introduce random response to add noise.

- Two servers: Platform & Tag server

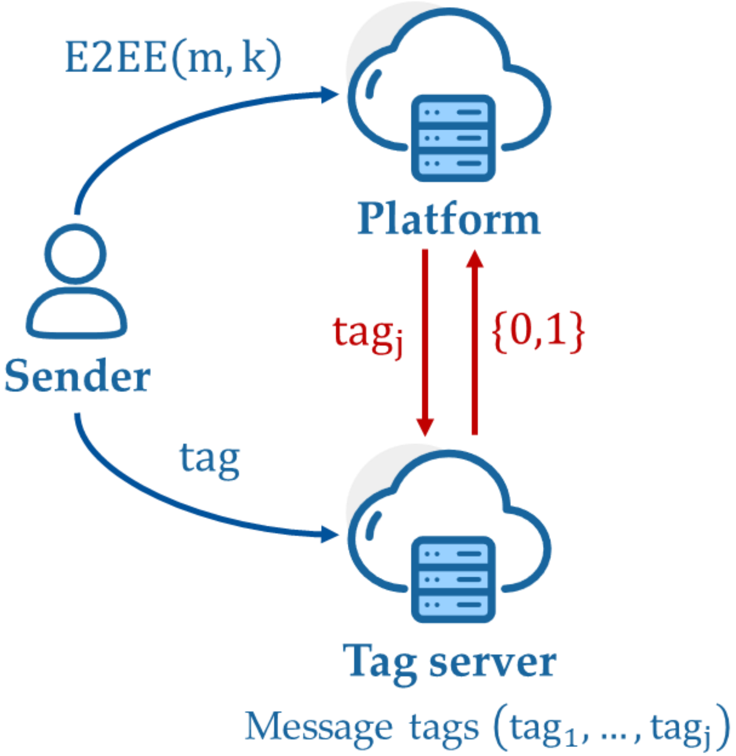


The Design: Noising the Traceback

Introduce random response to add noise.

- Two servers: Platform & Tag server
- Tag server responses a query as:

```
if $tag_j$ exists, return 1
else, return 0 w.p. $1 - \psi$
      return 1 w.p. $\psi$
```



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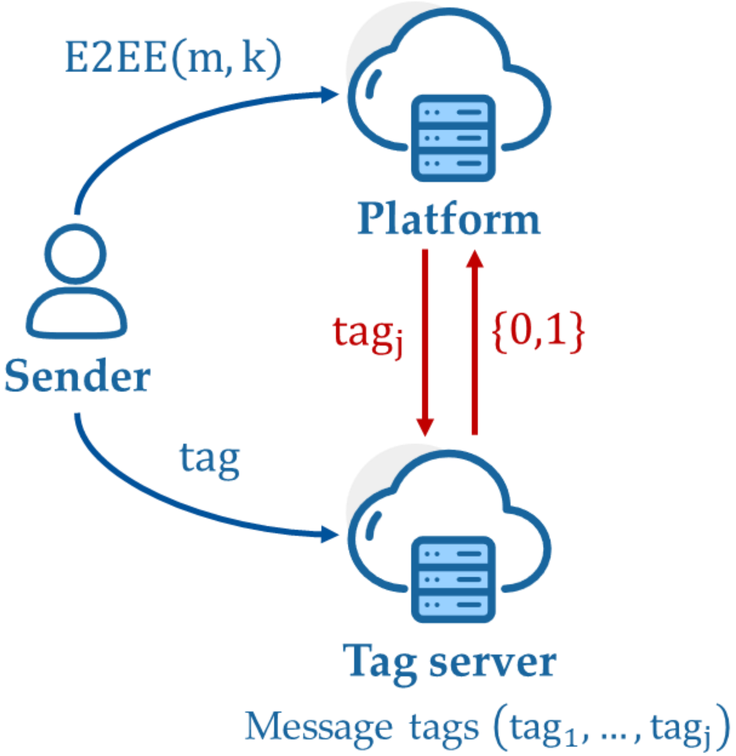

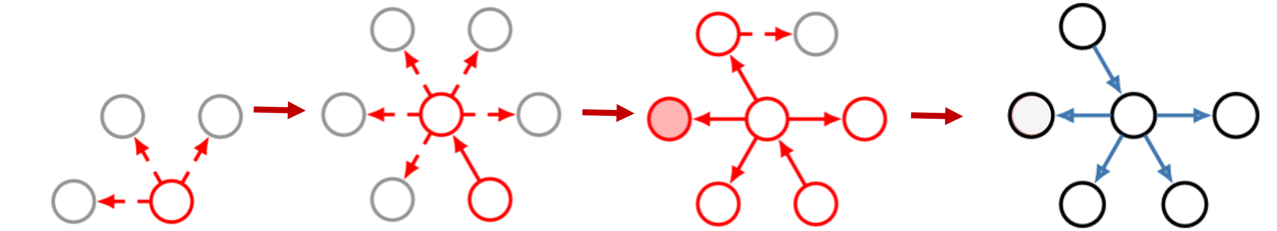

Round 1

Round 2

Round 3

Noised graph G^*_m

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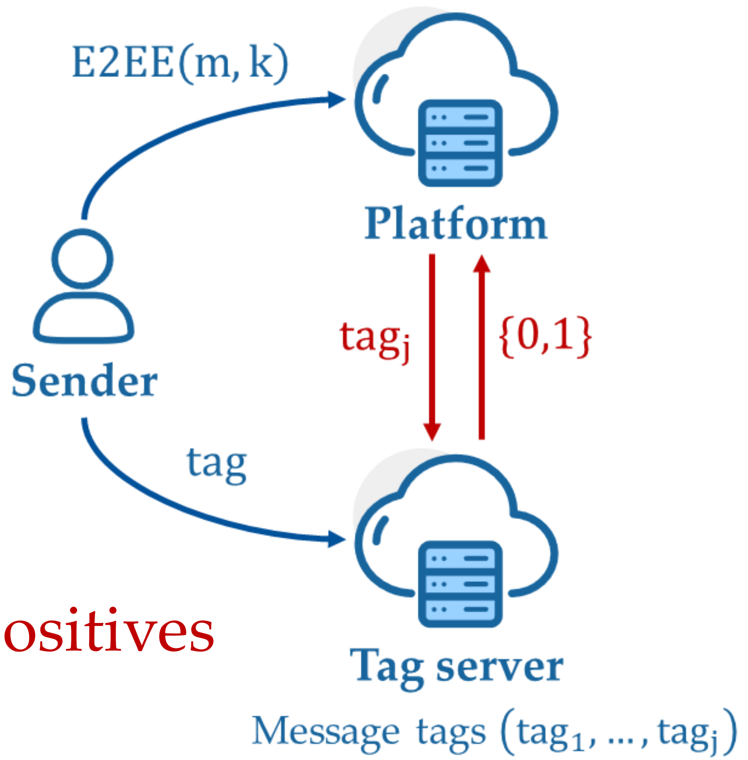
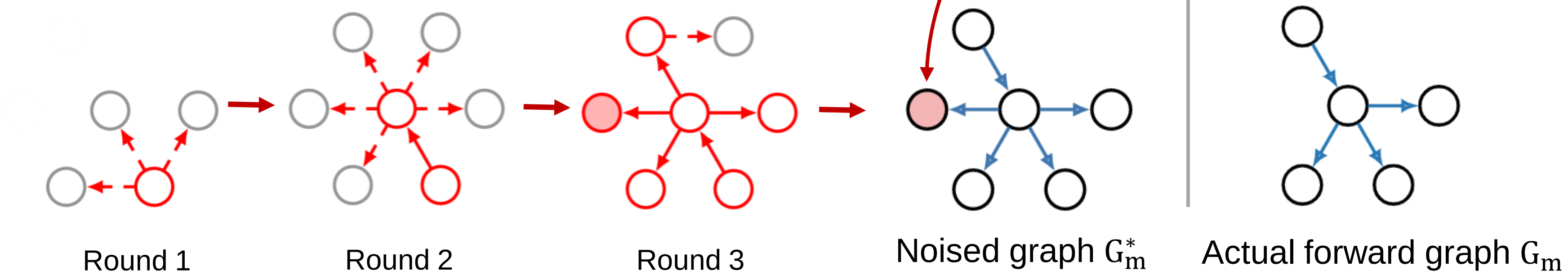
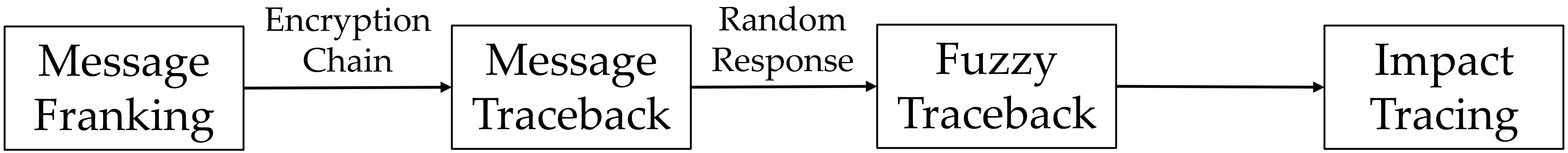


False positives



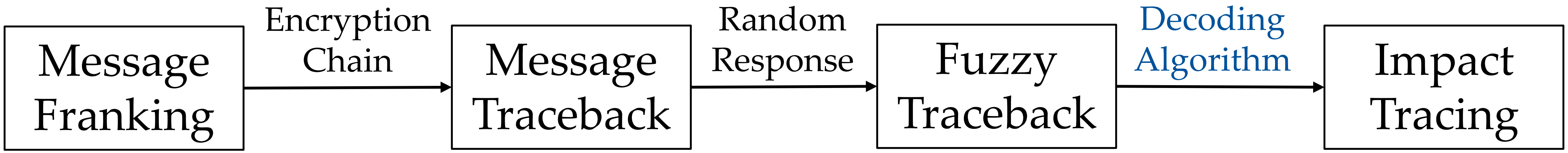
Remaining Concerns



Remaining Concerns

How to reveal influential spreaders from noised graph?

- Design a decoding algorithm to identify influential spreaders.



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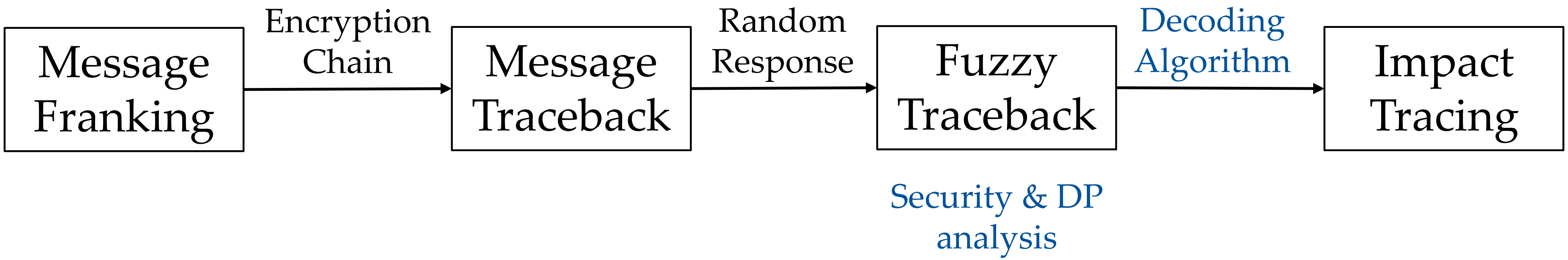
- Prove the noised graph satisfies differential privacy.



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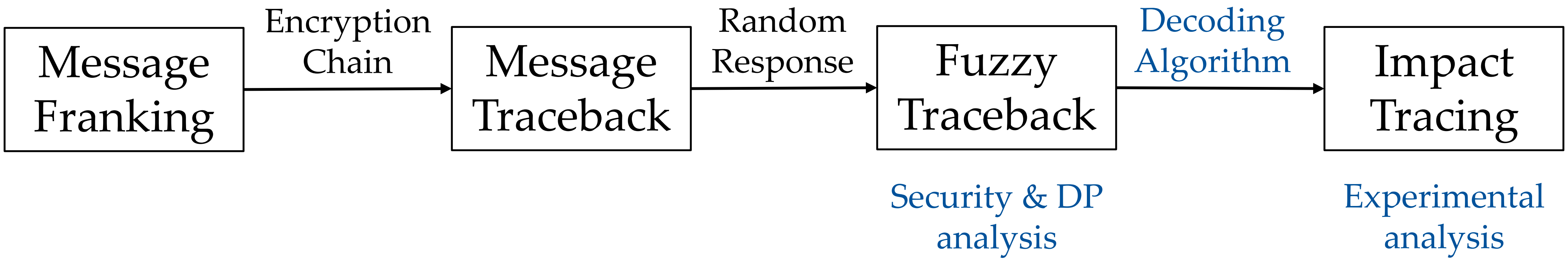

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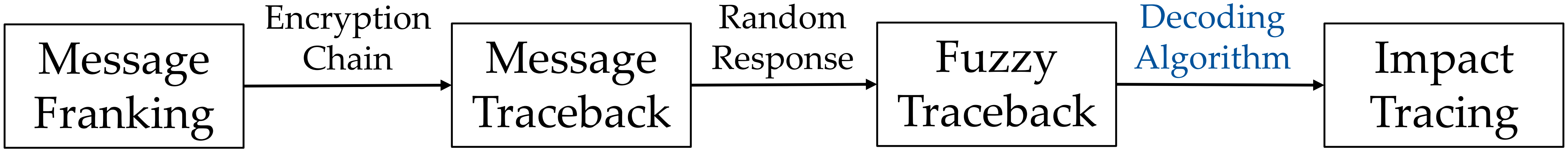


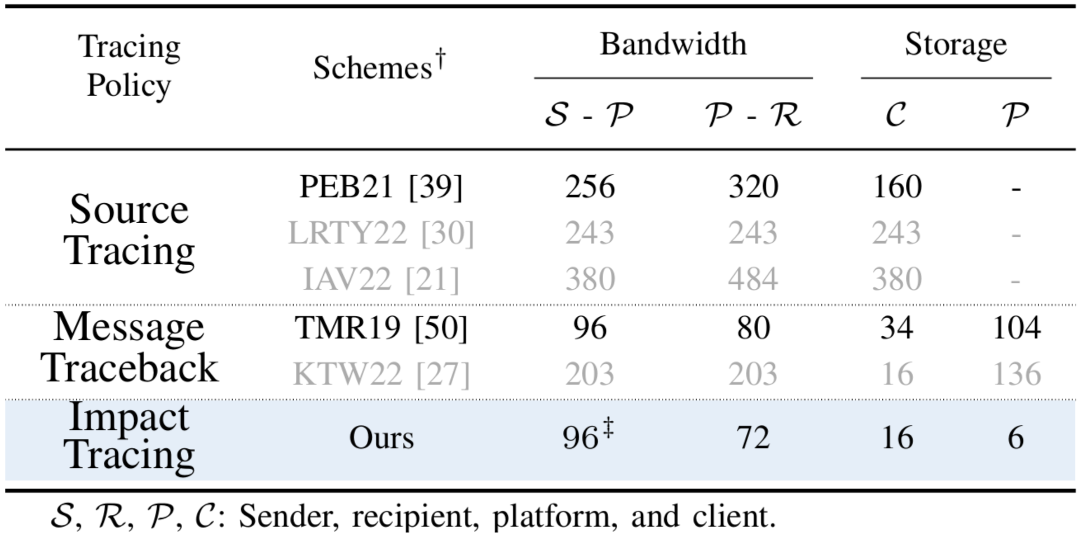
See paper for details.

Security & DP analysis

Experimental analysis

Performance

Bandwidth & Storage (Byte)



Tracing Policy	Schemes†	Bandwidth		Storage	
		$\mathcal{S}$ - $\mathcal{P}$	$\mathcal{P}$ - $\mathcal{R}$	$\mathcal{C}$	$\mathcal{P}$
Source Tracing	PEB21 [39]	256	320	160	-
	LRTY22 [30]	243	243	243	-
	IAV22 [21]	380	484	380	-
Message Traceback	TMR19 [50]	96	80	34	104
	KTW22 [27]	203	203	16	136
Impact Tracing	Ours	$96^{‡}$	72	16	6

$\mathcal{S}$, $\mathcal{R}$, $\mathcal{P}$, $\mathcal{C}$: Sender, recipient, platform, and client.

Store 1 billion messages: 5.6 GB

Performance

Bandwidth & Storage (Byte)

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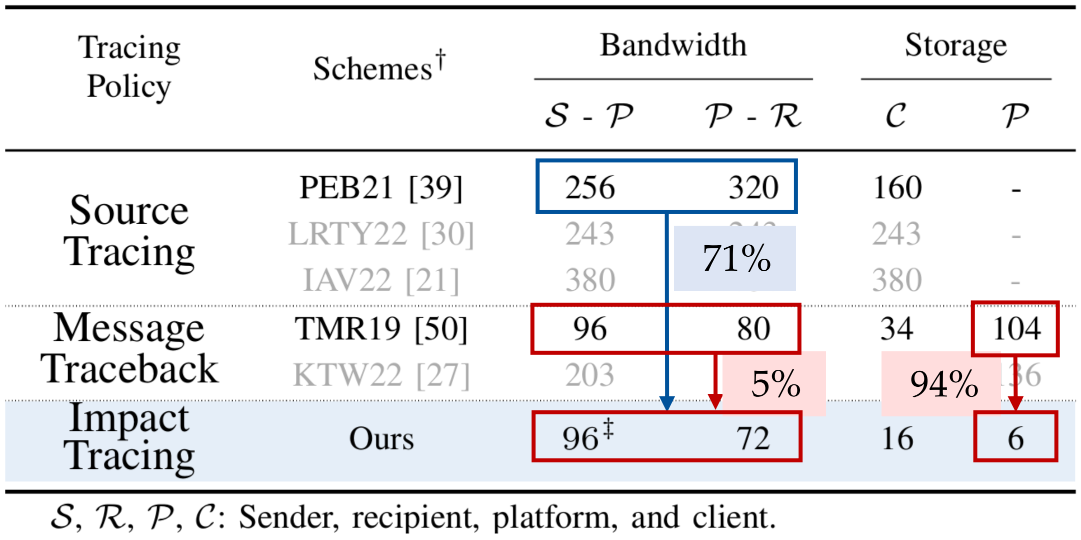

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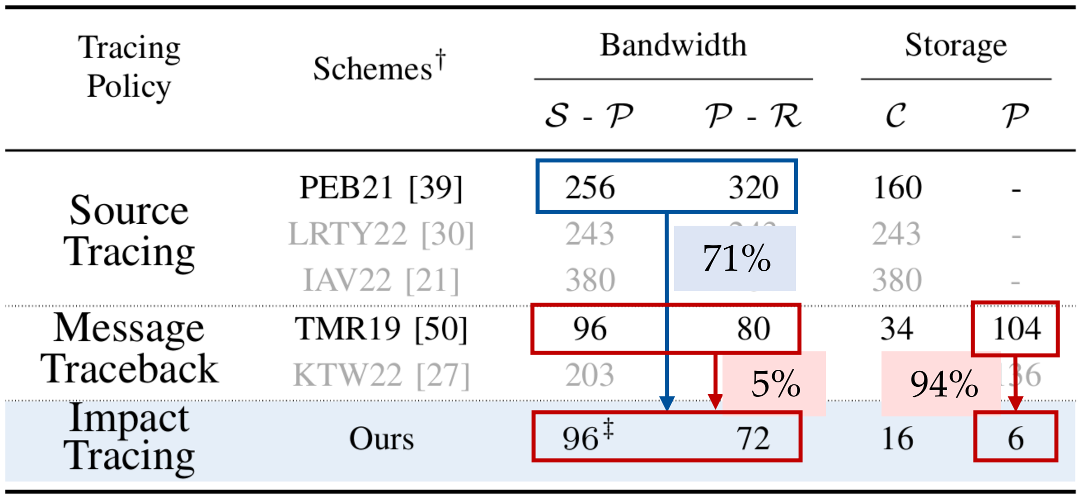

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5%

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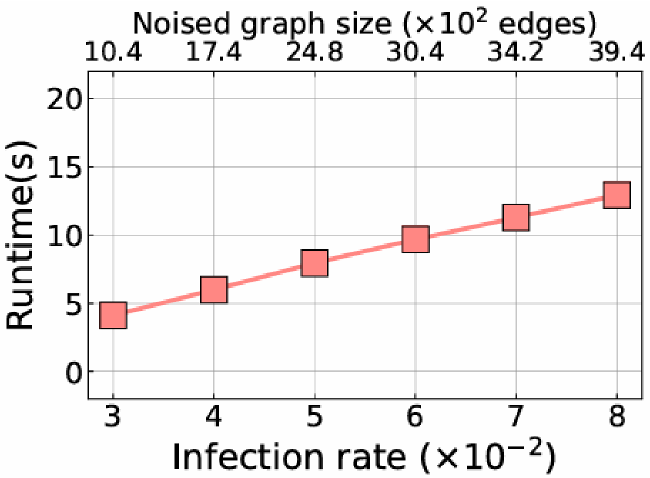
Runtime of tracing (s)



Trace graph with 4,000 edges: 15 s

Transmit 1-KB message: 0.3 ms

Performance

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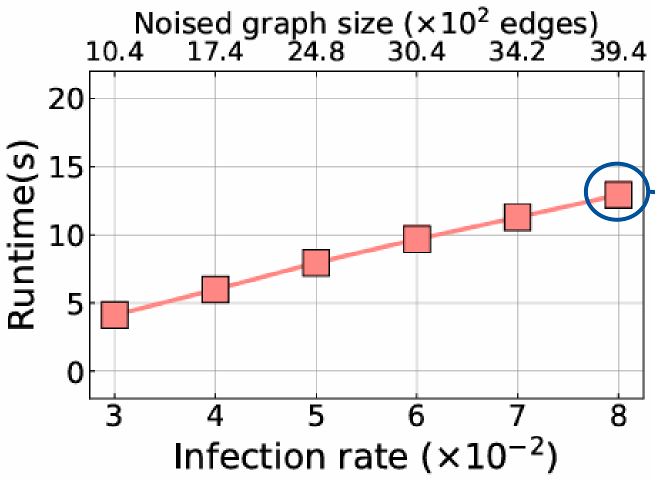

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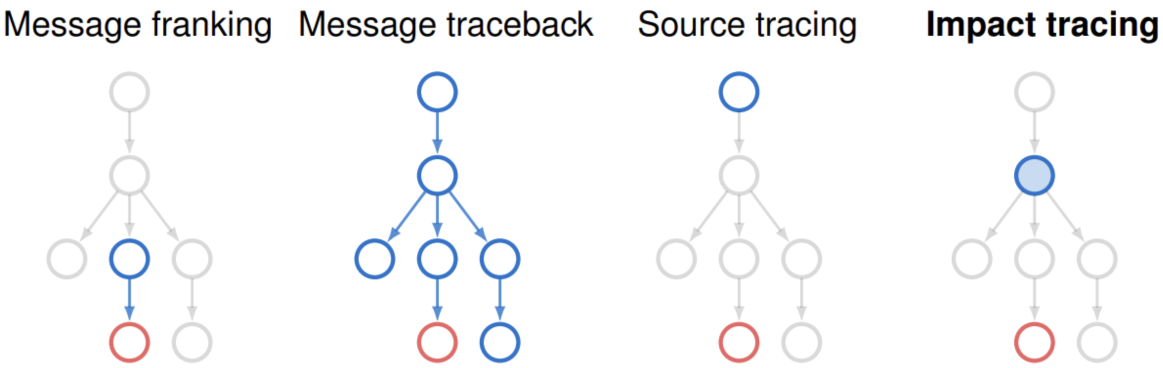
Summary

Introduce impact tracing: balances traceability and privacy.

Design fuzzy message traceback and decoding algorithm.

Analyze security, privacy, and utility formally.



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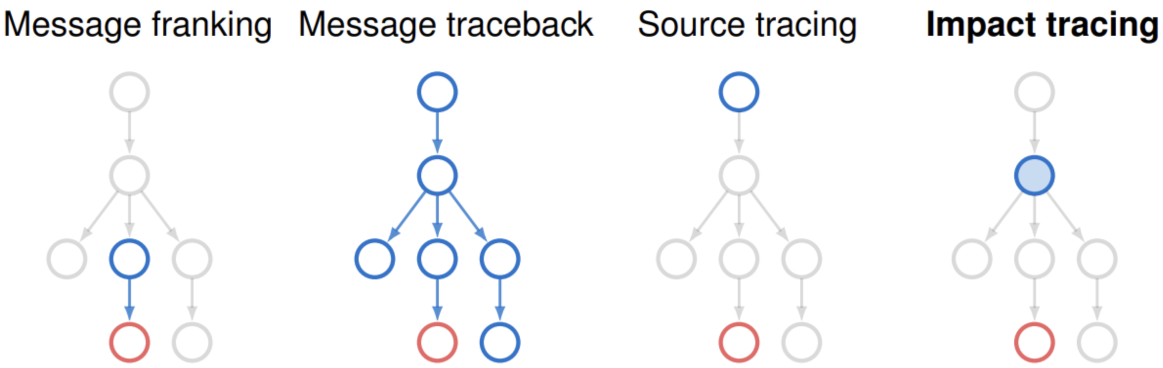


Scan for code.

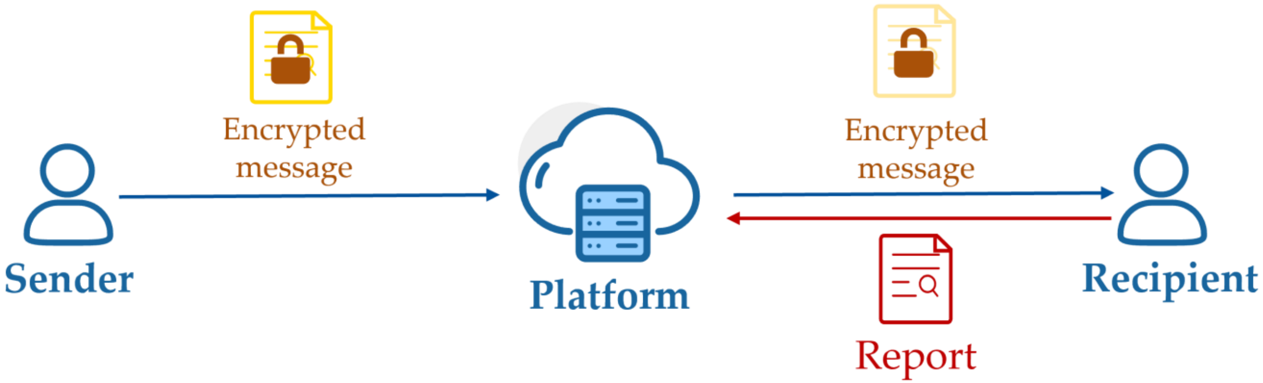
Thank for listening :) Any questions?

Bonus Slides

Message Franking

Message franking enables a recipient to <u>report a message</u>.

And, the platform can <u>authenticate</u> that the sender actually sent it.



Accountability: 1) Recipients cannot smear honest senders.

2) Senders cannot evade reporting.

Confidentiality: The platform learn nothing about unreported messages.

[Millican17,RWC] Challenges of E2E Encryption in Facebook Messenger

Simulation on Real-World Datasets

Influence evaluation

1. Simulate forwarding using SIR model.

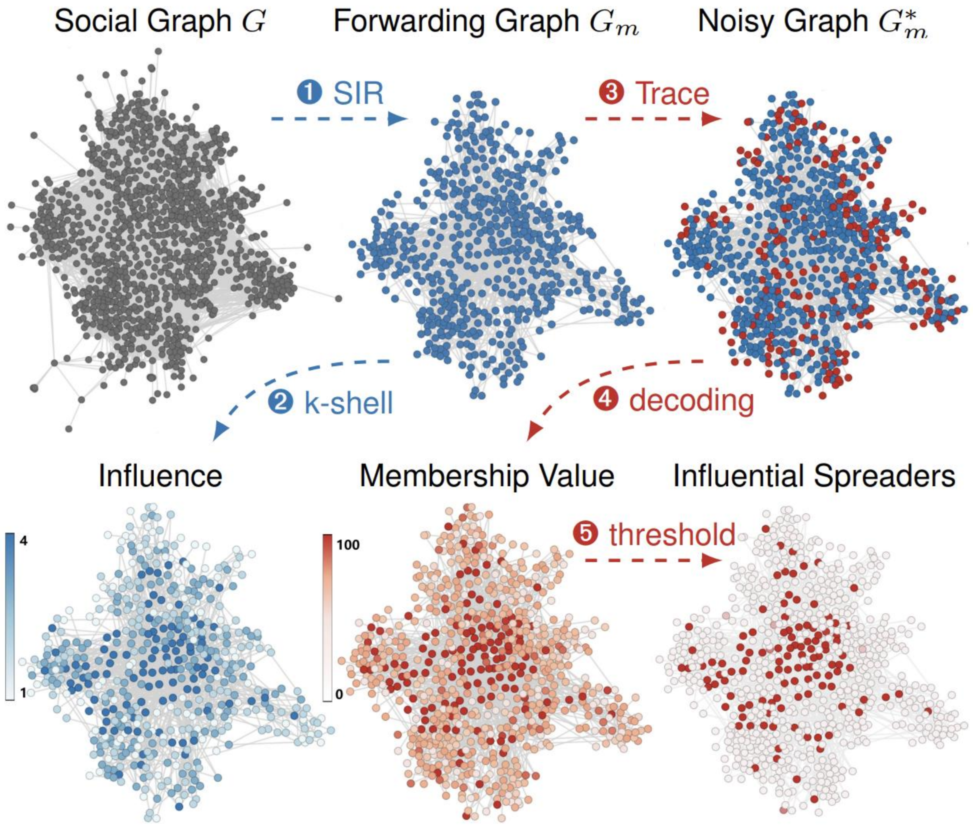
2. Evaluate vertices' impact using k-shell.

Impact tracing

3. Trace with fuzzy message traceback.

4. Decode the traced noisy graph.

5. Output a set of influential spreaders.



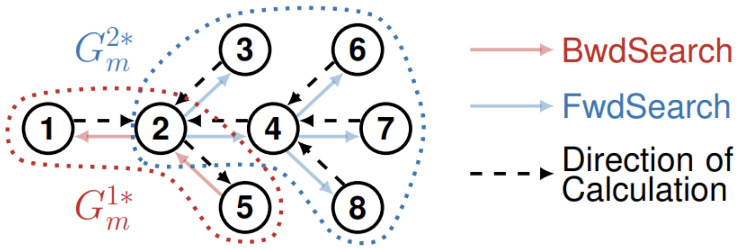
The Design: Decoding the Result

Decoding algorithm: Computes a fuzzy value for each vertex.

- The false positives of a vertex satisfy binomial distribution.

- A vertex has *only* one true precursor.

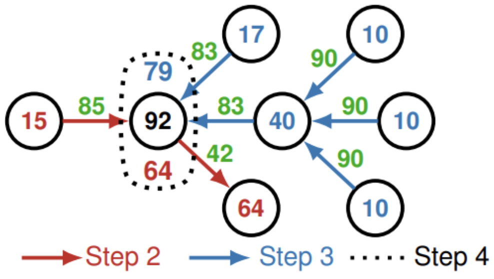
- A vertex is true positive if one of its descendants is true.



(a) llustration of G_m^{1*} and G_m^{2*}

Graph	Vertex	$n(v)$	$n^*(v)$	$a_v(\%)$
G_m^{1*}	v(2)	50	1	85
G_m^{2*}	v(2)	50	2	83
	v(4)	100	3	90
	v(5)	10	1	42

(b) Step 1: caculate α_v



(c) Step 2-4: caculate β_v^1, β_v^2, and μ_v

IAS-DP: Defining Privacy

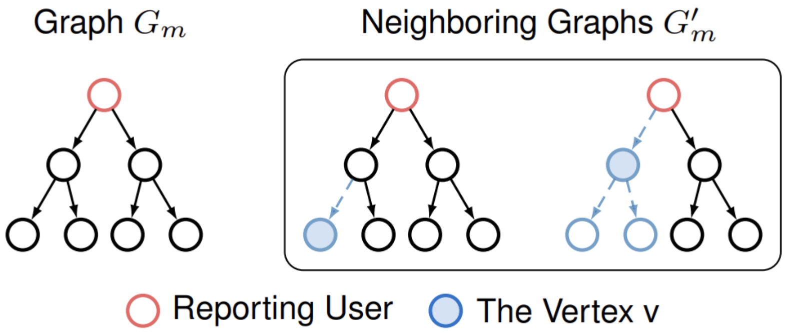
Individualized Asymmetric Subtree Differential Privacy

- **Individualized**: Privacy budgets vary per user.
- **Asymmetric**: Traceability adopts one-side noise.
- **Subtree**: All impacts caused by one user on one forwarding graph.

Definition 2 (ε_v-IAS-DP). A randomized algorithm $\mathcal{M}$ is ε_v-IAS-DP if given a graph G the following equation holds for any $S \in Range(\mathcal{M})$ and neighboring subgraph pair (G_m, G'_m), where G'_m is obtained by removing a subtree $tree(v)$ in G_m.

$$\Pr\left[\mathcal{M}(G_m) = S\right] \leq e^{\varepsilon_v} \cdot \Pr[\mathcal{M}(G'_m) = S],$$

where ε_v is the privacy budget for vertex v.



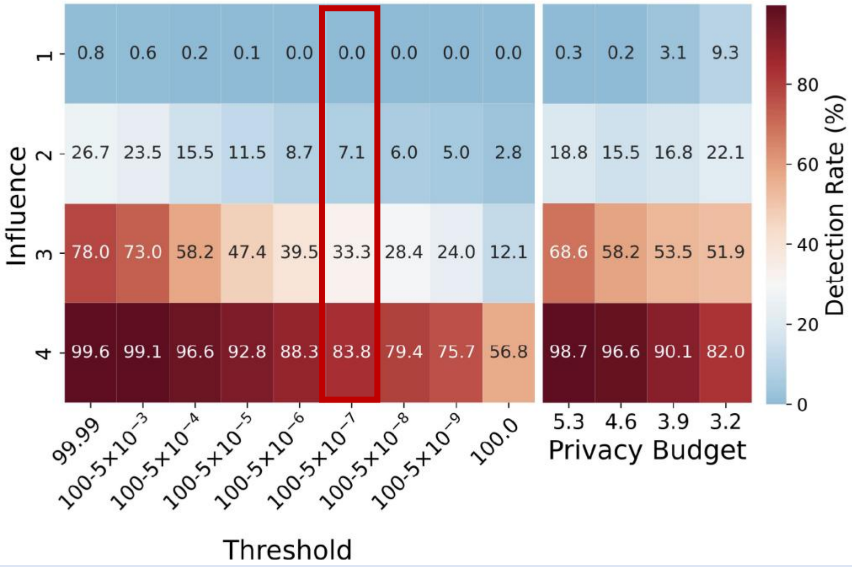
Theorem 1. The fuzzy message traceback scheme satisfies ε_v-IAS-DP, where $\boxed{\varepsilon_v = \ln(1/\psi^n)}$, n is the number of edges in $tree(v)$, and ψ is the FPR of random response.

Evaluating Utility & Privacy

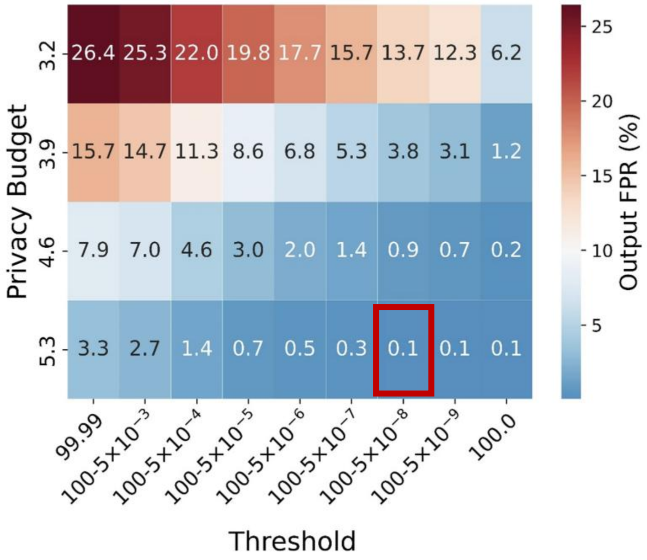
Detection rate: The output contains as most influential users as possible.

Output FPR: The output should contain as few false positives as possible.

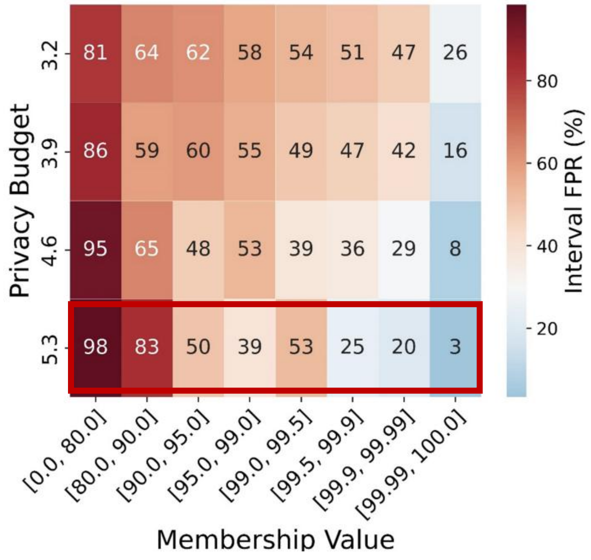
Interval FPR: Non-influential users should be hidden by sufficient noise.



Influence	99.99	$100-5\times10^{-3}$	$100-5\times10^{-4}$	$100-5\times10^{-5}$	$100-5\times10^{-6}$	$100-5\times10^{-7}$	$100-5\times10^{-8}$	$100-5\times10^{-9}$	100.0	5.3	4.6	3.9	3.2
1	0.8	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.2	3.1	9.3
2	26.7	23.5	15.5	11.5	8.7	7.1	6.0	5.0	2.8	18.8	15.5	16.8	22.1
3	78.0	73.0	58.2	47.4	39.5	33.3	28.4	24.0	12.1	68.6	58.2	53.5	51.9
4	99.6	99.1	96.6	92.8	88.3	83.8	79.4	75.7	56.8	98.7	96.6	90.1	82.0



Privacy Budget	99.99	$100-5\times10^{-3}$	$100-5\times10^{-4}$	$100-5\times10^{-5}$	$100-5\times10^{-6}$	$100-5\times10^{-7}$	$100-5\times10^{-8}$	$100-5\times10^{-9}$	100.0
3.2	26.4	25.3	22.0	19.8	17.7	15.7	13.7	12.3	6.2
3.9	15.7	14.7	11.3	8.6	6.8	5.3	3.8	3.1	1.2
4.6	7.9	7.0	4.6	3.0	2.0	1.4	0.9	0.7	0.2
5.3	3.3	2.7	1.4	0.7	0.5	0.3	0.1	0.1	0.1



Privacy Budget	[0.0, 80.0]	[80.0, 90.0]	[90.0, 95.0]	[95.0, 99.0]	[99.0, 99.5]	[99.5, 99.9]	[99.9, 99.99]	[99.99, 100.0]
3.2	81	64	62	58	54	51	47	26
3.9	86	59	60	55	49	47	42	16
4.6	95	65	48	53	39	36	29	8
5.3	98	83	50	39	53	25	20	3

Identifies 84% of the most influential spreaders and no the least influential users with 99.9% correctness (i.e., less than 0.25 false positives on average).