Out-of-Band Authentication in Group Messaging: Computational, Statistical, Optimal

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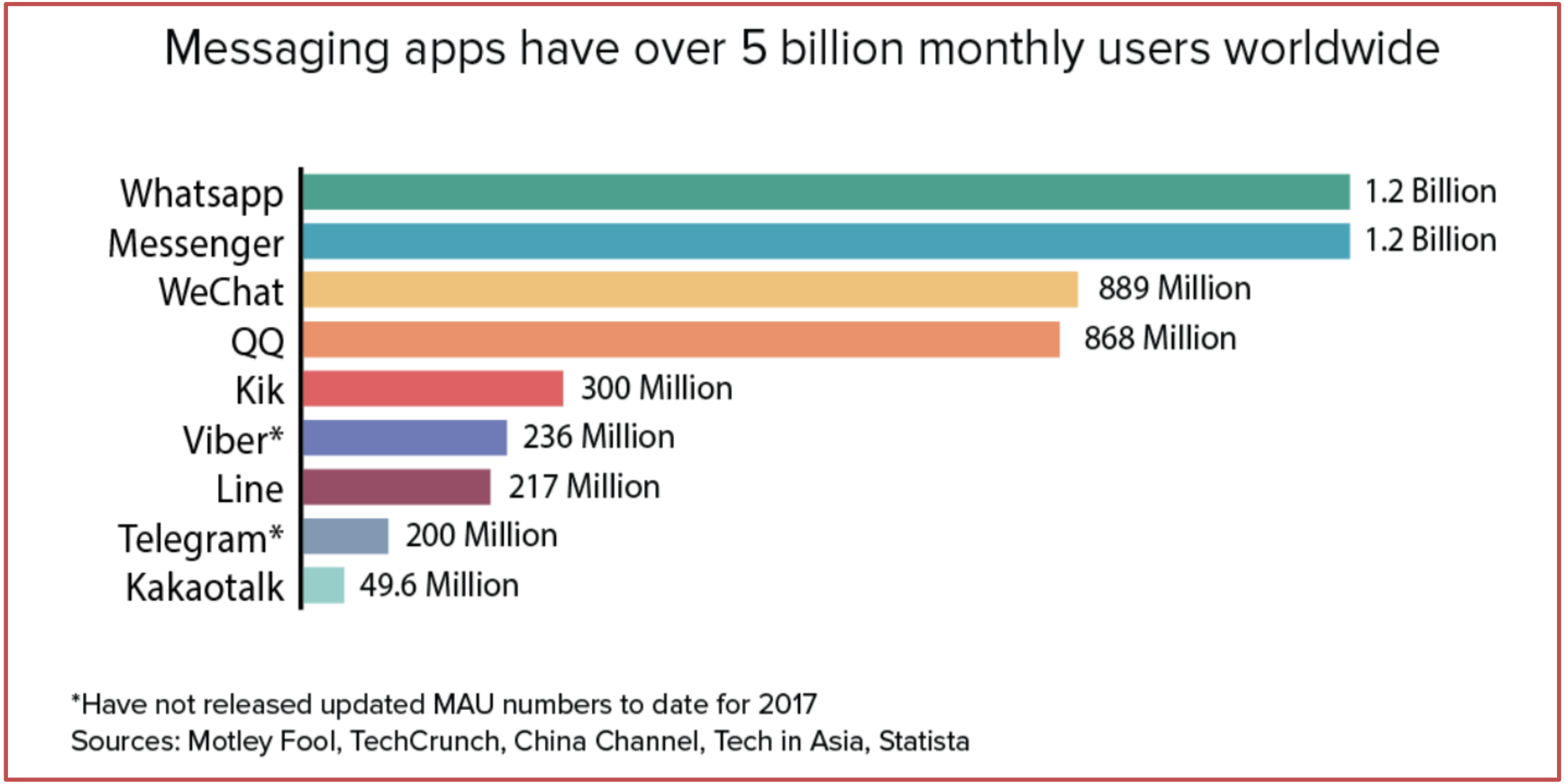
Messaging is Popular…



Major Effort: E2E-Encrypted Messaging

- Government surveillance and/or coercion
- Untrusted or corrupted messaging servers

Key challenge:
Detecting **man-in-the-middle attacks** when setting up E2E-encrypted channels

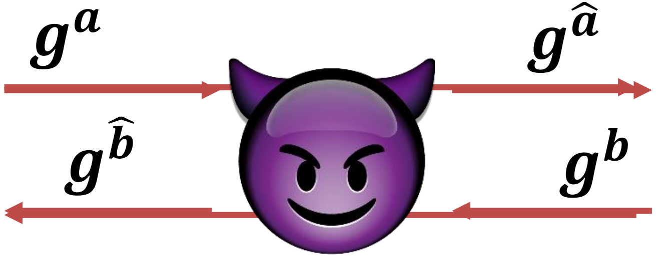
Man-in-the-Middle Attacks

Alice’s phone
Bob’s phone

Man-in-the-Middle Attacks

- Impossible to detect without any setup

Alice’s phone



Bob’s phone

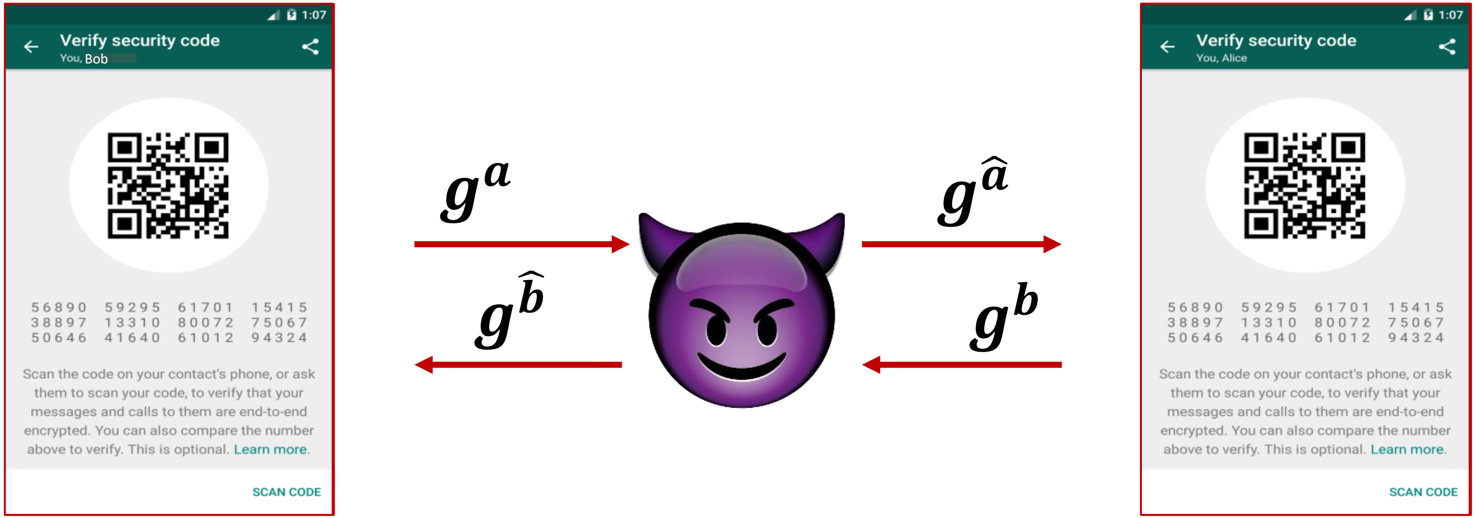
Impractical to assume a trusted PKI in messaging platforms…

Out-of-Band Authentication

Practical to assume: Users can "out-of-band" authenticate one short value

Alice's phone

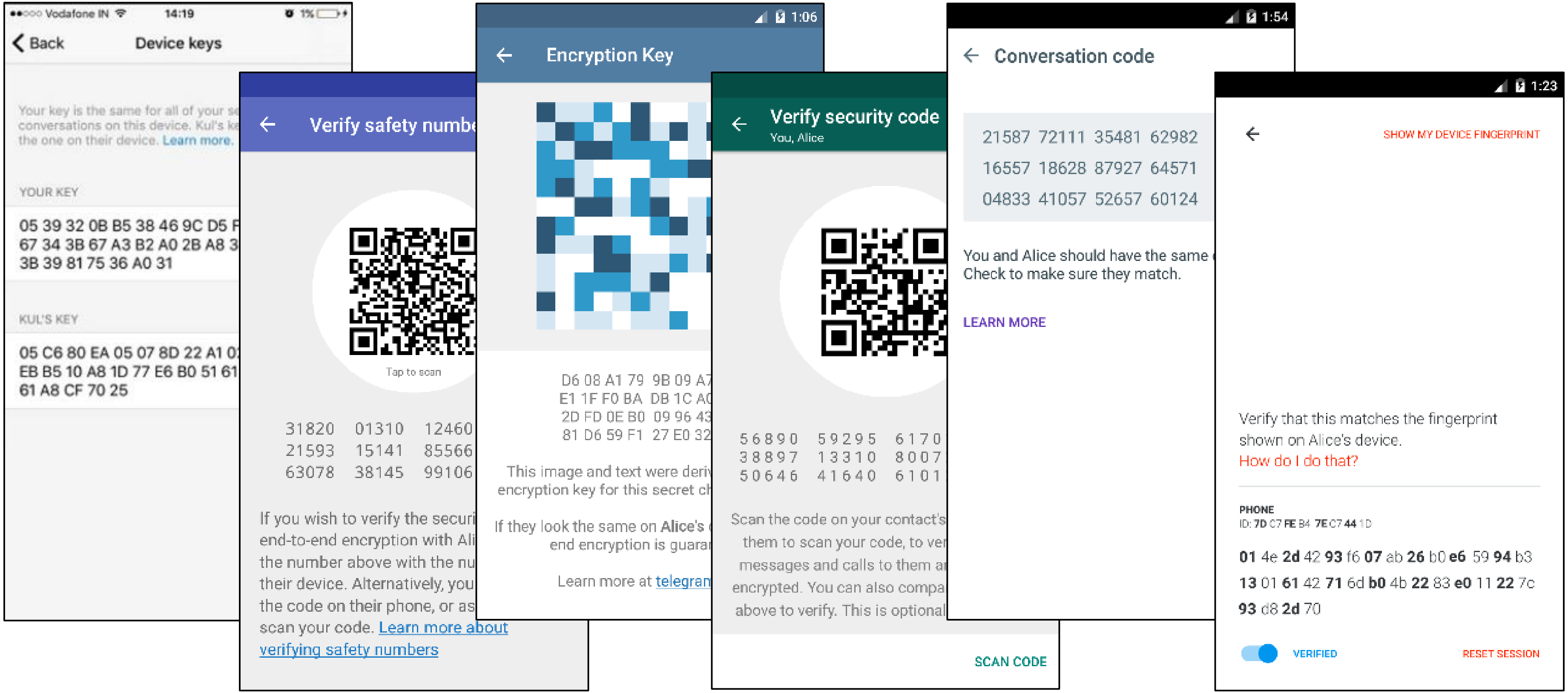
Bob's phone



- Users can compare a short string displayed on their devices
- Assuming that they recognize each other's voice, this is a low-bandwidth authenticated channel

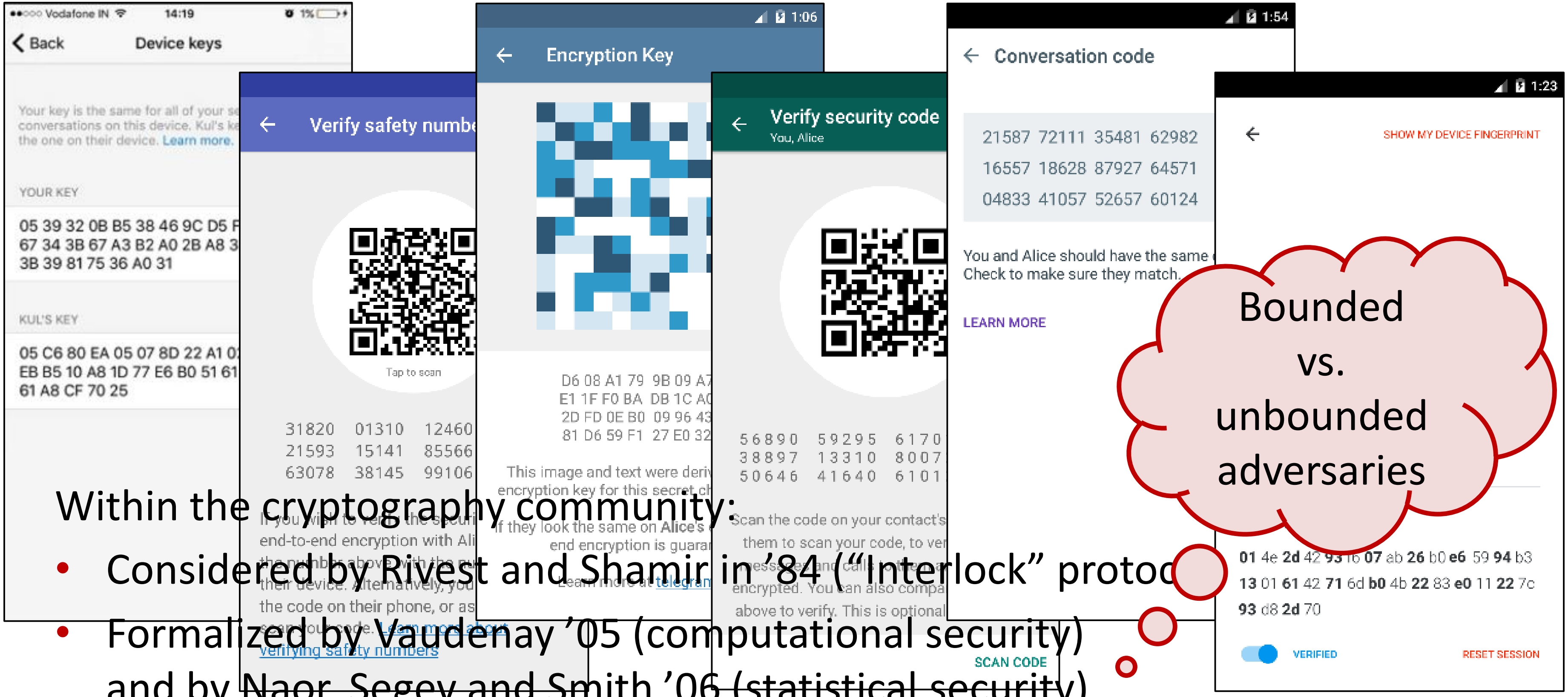
Out-of-Band Authentication

Facebook Telegram Allo



Signal WhatsApp Wire

Out-of-Band Authentication



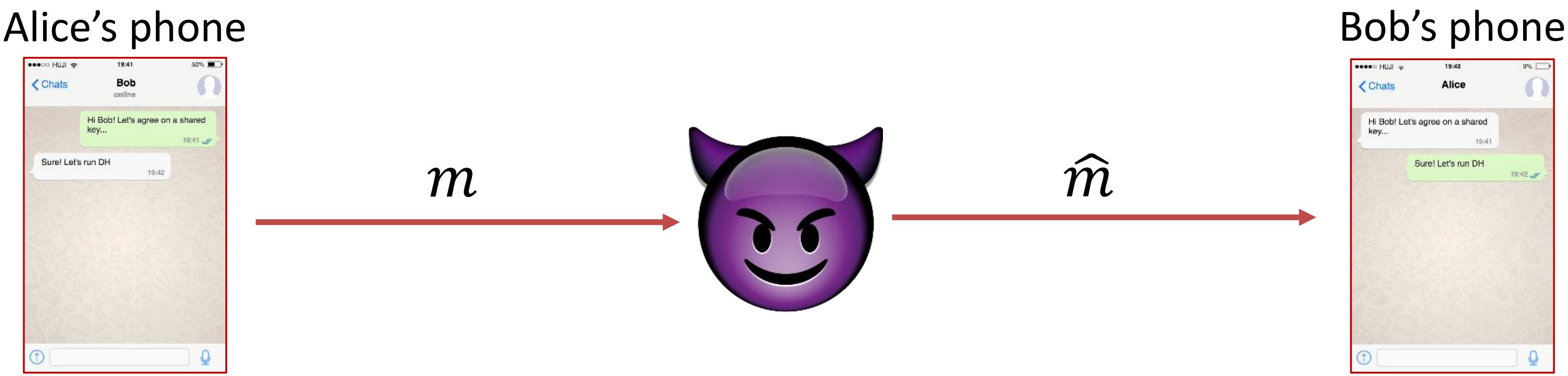
Bounded vs. unbounded adversaries

Within the cryptography community:

- Considered by Rivest and Shamir in '84 ("Interlock" protoc
- Formalized by Vaudenay '05 (computational security) and by Naor, Segev and Smith '06 (statistical security)

The User-to-User Setting

- An equivalent problem: Detecting MitM attacks in message authentication



Detect with prob. $1-\epsilon$ whenever $\hat{m} \neq m$

$\Rightarrow$ Given a shared key: MAC the message

$\Leftarrow$ Given a message authentication protocol: Run any key exchange protocol and authenticate the transcript

The User-to-User Setting

Alice's phone

g^{a} →

← $g^{\hat{b}}$

$g^{\hat{a}}$ →

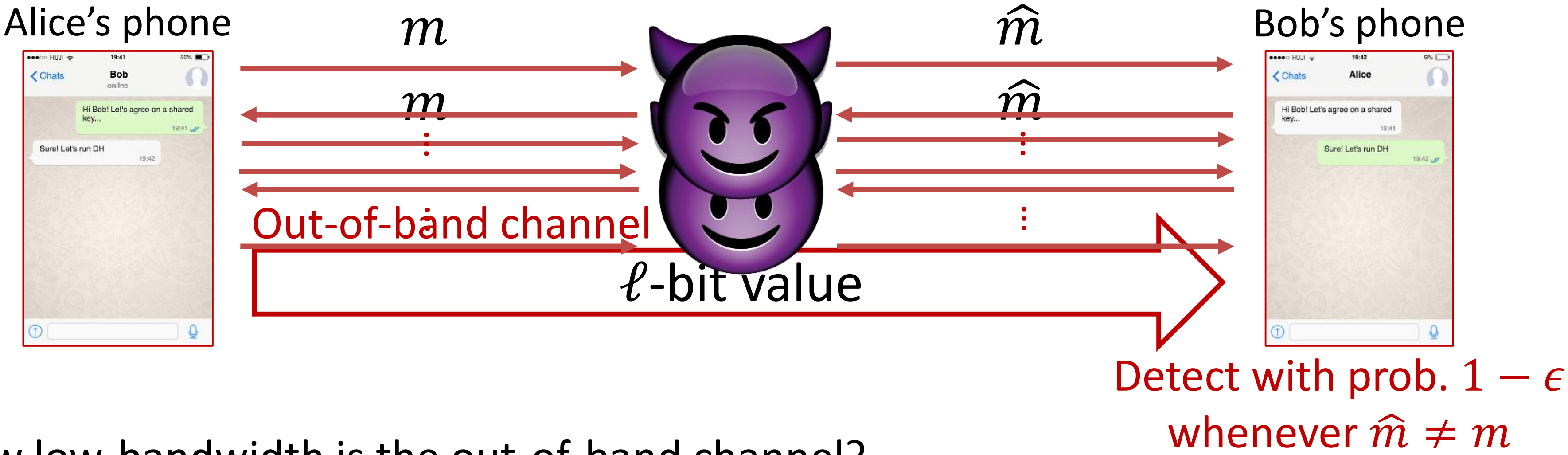
← g^{b}

Bob's phone

$$m = g^{a} || g^{\hat{b}}$$

$$\hat{m} = g^{\hat{a}} || g^{b}$$

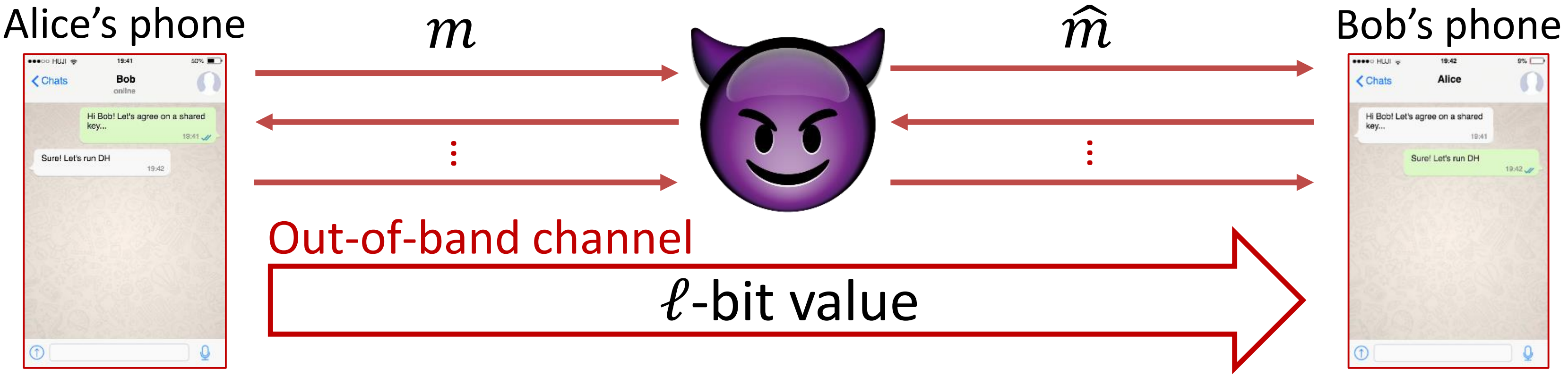
The User-to-User Setting



How low-bandwidth is the out-of-band channel?

- WhatsApp\Signal $\ell = 200$ bits (60 digits)
- Telegram $\ell = 288$ bits (64 characters)
- …
- Lower bound: $\ell \geq \log(1/\epsilon)$ [PV06]

The User-to-User Setting



Detect with prob. $1 - \epsilon$
whenever $\hat{m} \neq m$

Goal: Optimal tradeoff between ℓ and ϵ

Minimize user effort ⟷ **Maximize security**

User-to-User Bounds

	Protocols	Lower Bounds
Computational Security [Vau05, PV06]	$\log(1/\epsilon)$	$\log(1/\epsilon) - O(1)$
Statistical Security [NSS06]	$2\log(1/\epsilon) + O(1)$	$2\log(1/\epsilon) - O(1)$

This Talk: The Group Setting

User-to-User Setting

✓ Tightly characterized

✓ Practical protocols deployed

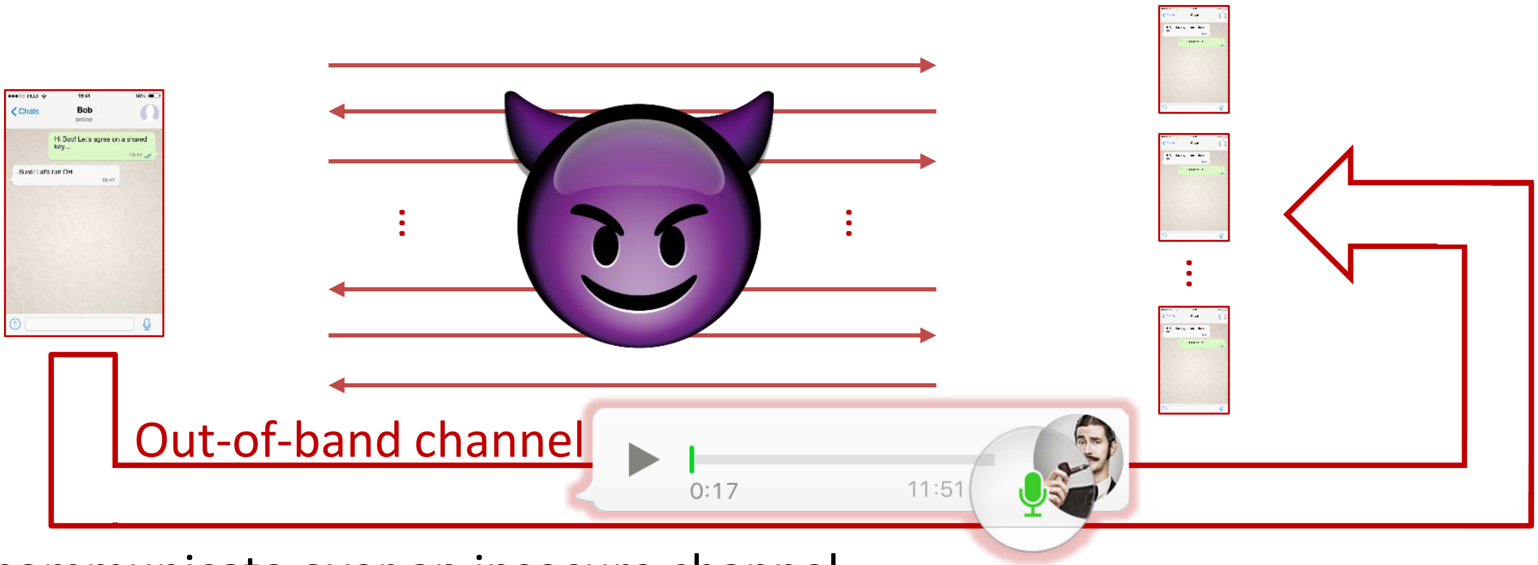
Group Setting

? Not yet studied

✗ Impractical protocols deployed

Our Contributions

A framework modeling out-of-band authentication in the group setting



- Users communicate over an insecure channel
- Group administrator can out-of-band authenticate one short value to all users
- Consistent with and supported by existing messaging platforms

Our Contributions

A framework modeling out-of-band authentication in the group setting

Tight bounds for out-of-band authentication in the group setting

	Protocols	Lower Bounds
Computational Security	$\log(1/\epsilon) + \log k$	$\log(1/\epsilon) + \log k - O(1)$

k – number of receivers

Our computationally-secure protocol is practically relevant,
and substantially improves the currently-deployed protocols:

E.g., $k = 32$ and $\epsilon = 2^{-80}$: $32 \times 85 = 2720$ bits vs. 85 bits!!

Talk Outline

- Communication model & notions of security
- The naïve protocol
- Our protocols & lower bounds

	Protocols	Lower Bounds
Computational Security	$\log(1/\epsilon) + \log k$	$\log(1/\epsilon) + \log k - O(1)$
Statistical Security	$(k+1) \cdot \left(\log(1/\epsilon) + \log k + O(1)\right)$	$(k+1) \cdot \log(1/\epsilon) - k$

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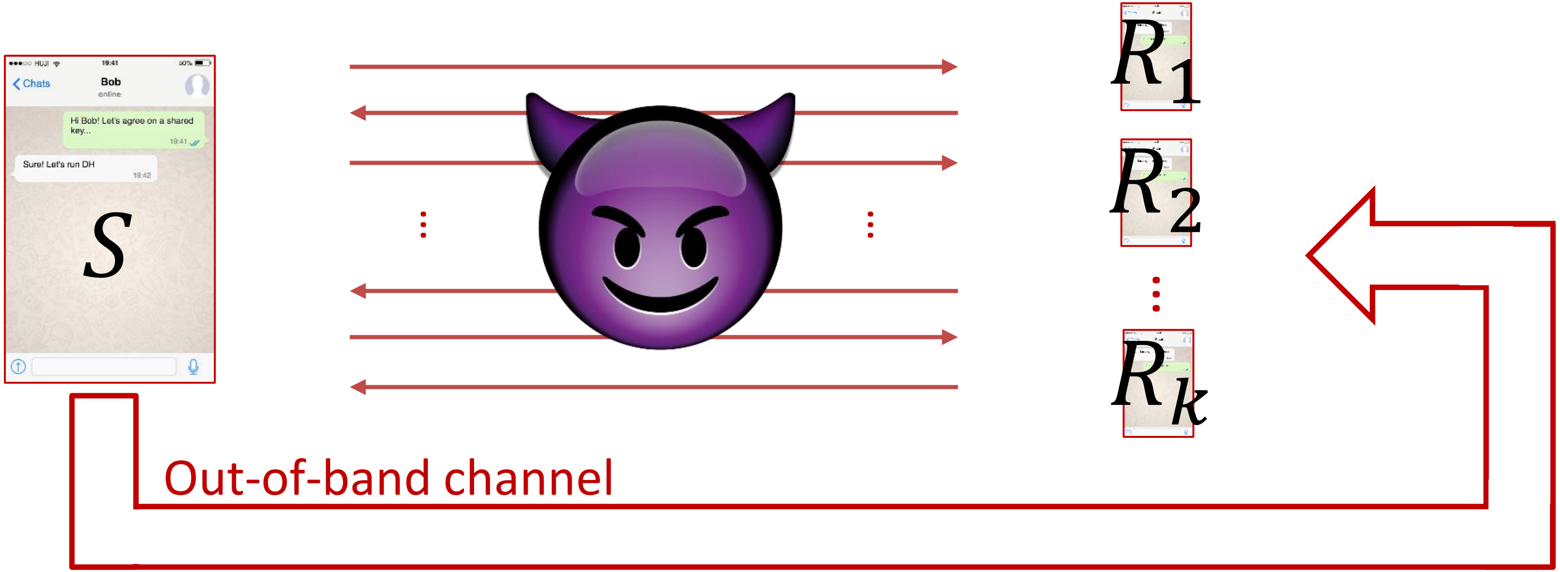
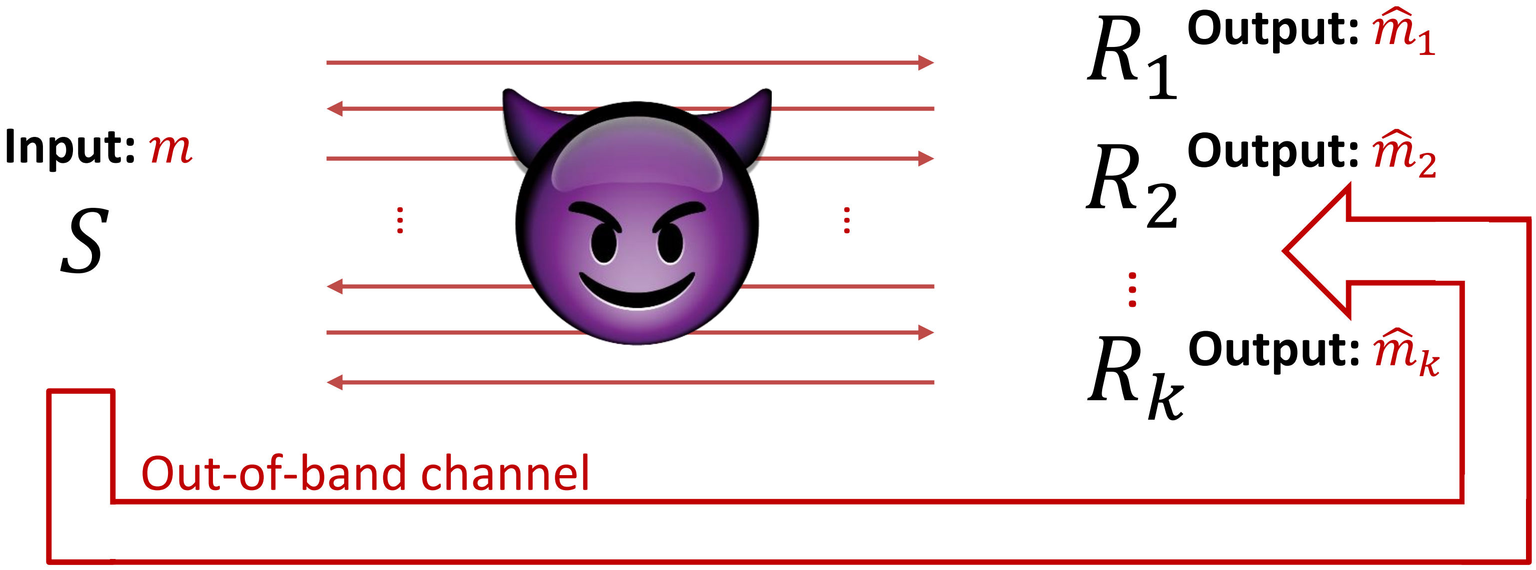
Communication Model



- Insecure channel: Adversary can read, remove and insert messages
- Out-of-band channel:
  Adversary can read, remove and delay messages, for all or for some of the users
  Adversary cannot modify messages/insert new ones in an undetectable manner

Correctness & Security



- **Correctness:** In an honest execution $\forall i\colon\ \hat{m}_i = m$
- **Unforgeability:** $\Pr[\exists i\colon\ \hat{m}_i \notin \{m, \perp\}] \leq \epsilon + \nu(\lambda)$
- Computational vs. statistical security

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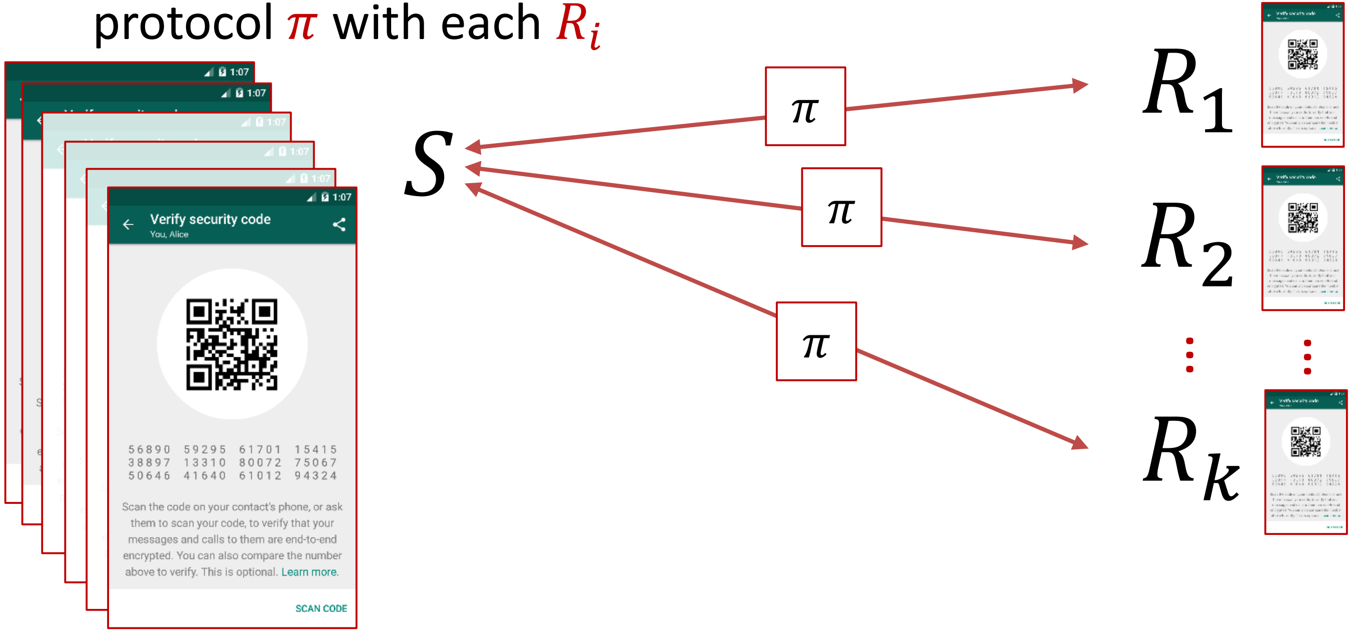
The Naïve Protocol

- Independently invoke a user-to-user protocol π with each R_i



- S out-of-band authenticates at least $k \cdot \log(k/\epsilon)$ bits
- E.g., $k = 2^{10}$ and $\epsilon = 2^{-80}$: $2^{10} \times 90$ bits

  $k = 32$ and $\epsilon = 2^{-80}$: 32×85 bits

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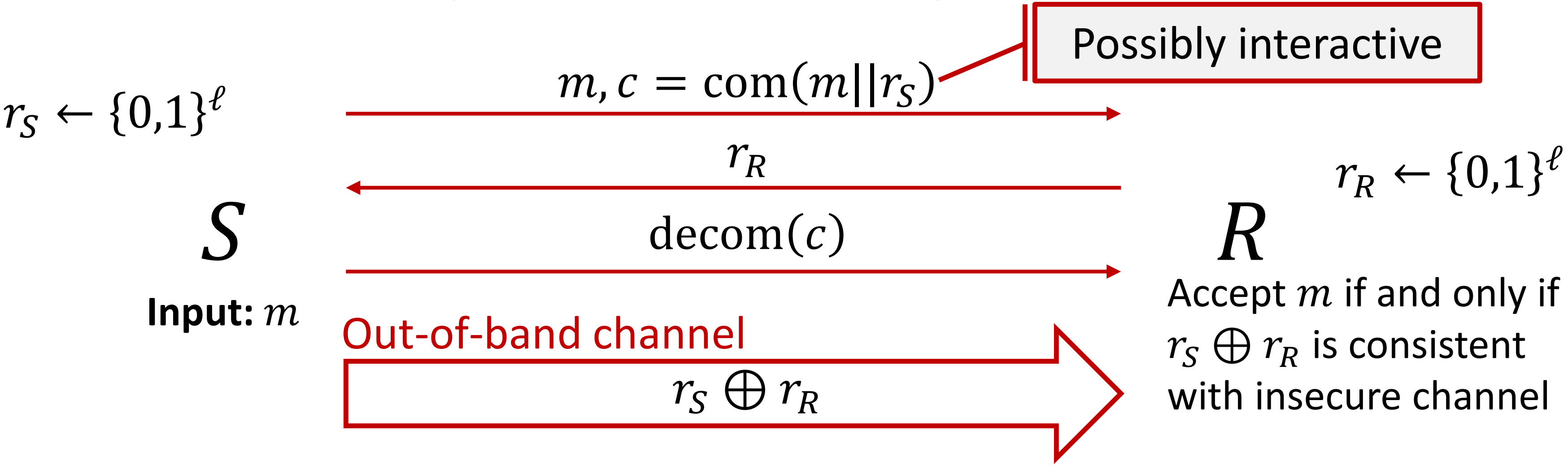
Warm-Up: Vaudenay's Protocol

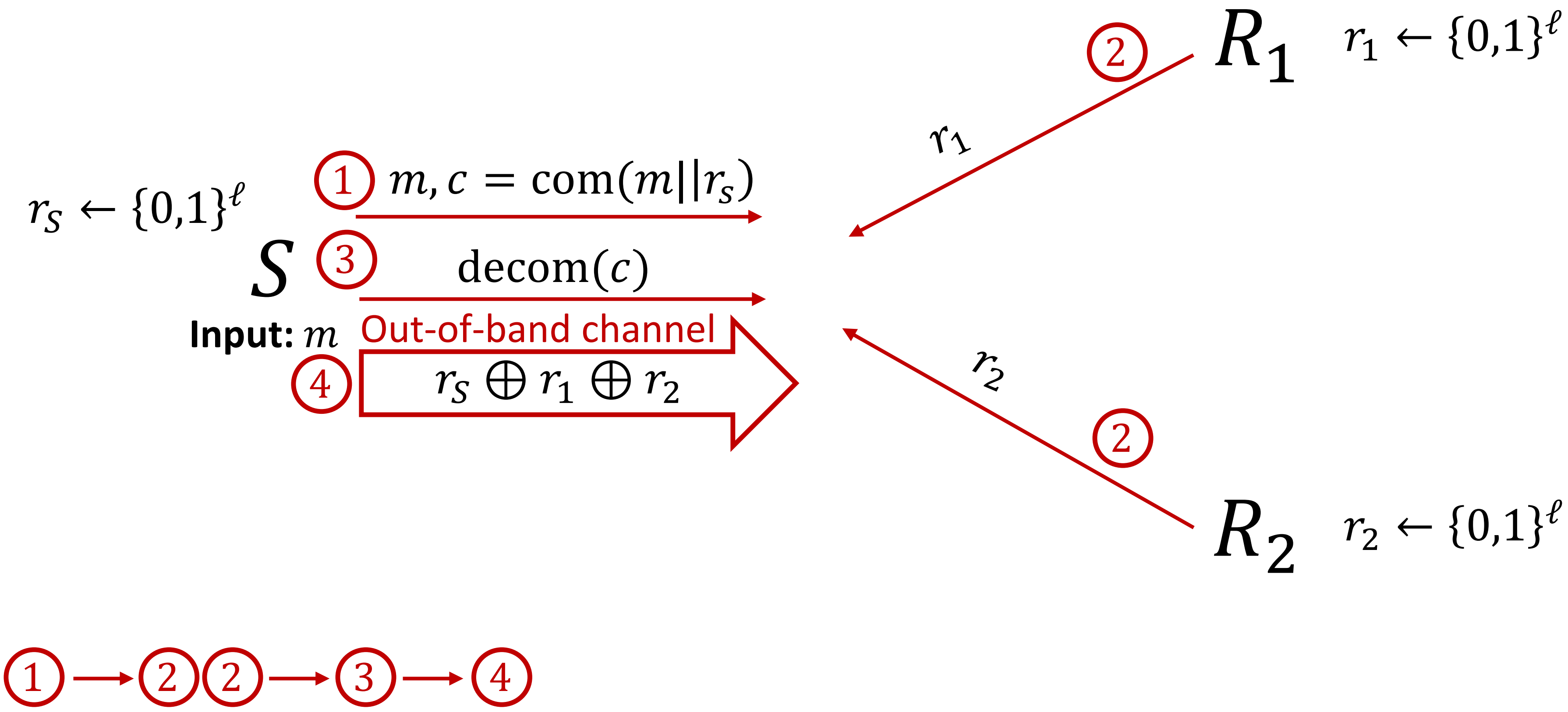


Theorem [Vau05,LN06]:
If $(\mathrm{com}, \mathrm{decom})$ is non-malleable then for any $\ell \in \mathbb{N}$ it holds that $\epsilon = 2^{-\ell}$

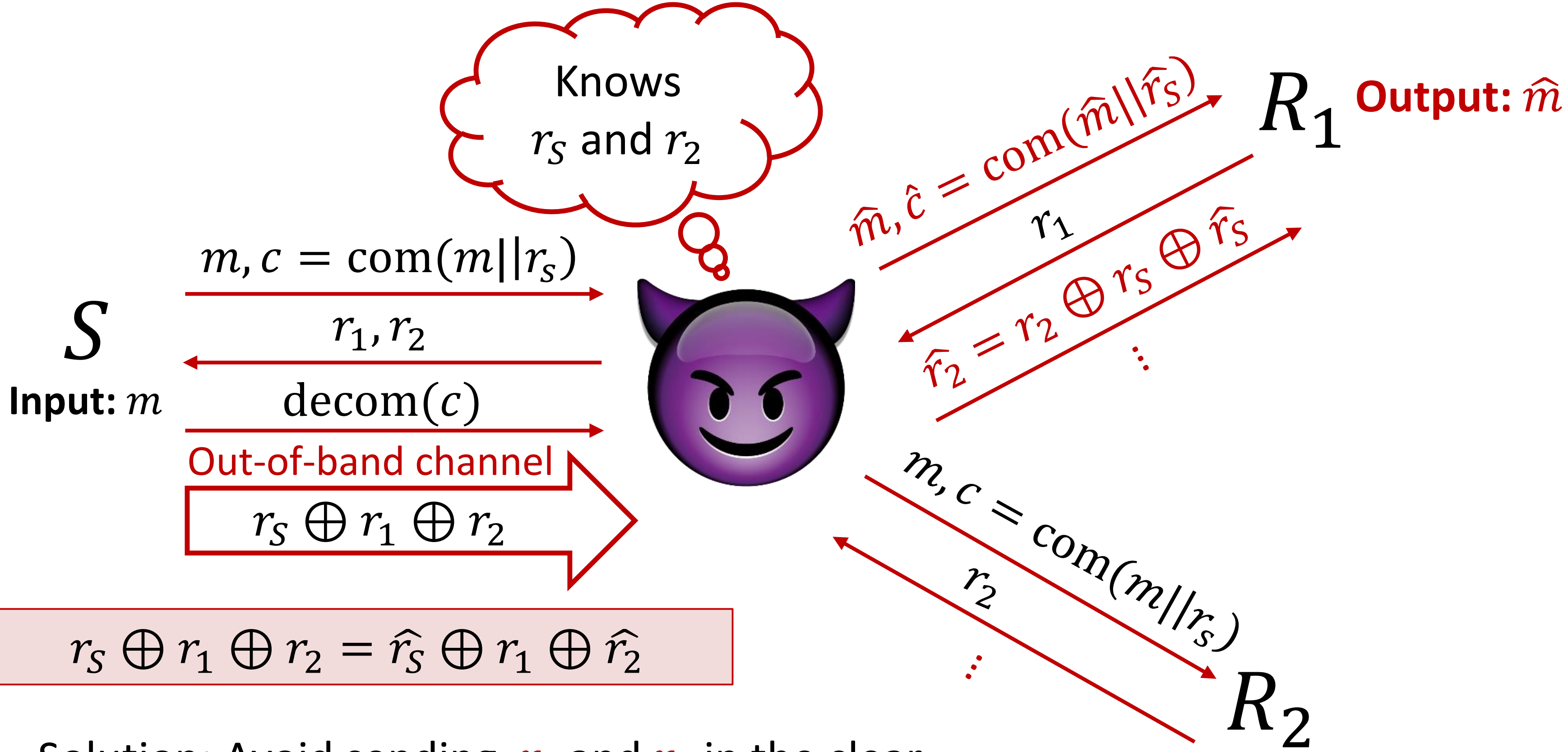
Proof sketch:

- Consider all possible synchronizations of a MitM attack
- Reduce each one to the security of the commitment scheme

Our First Attempt



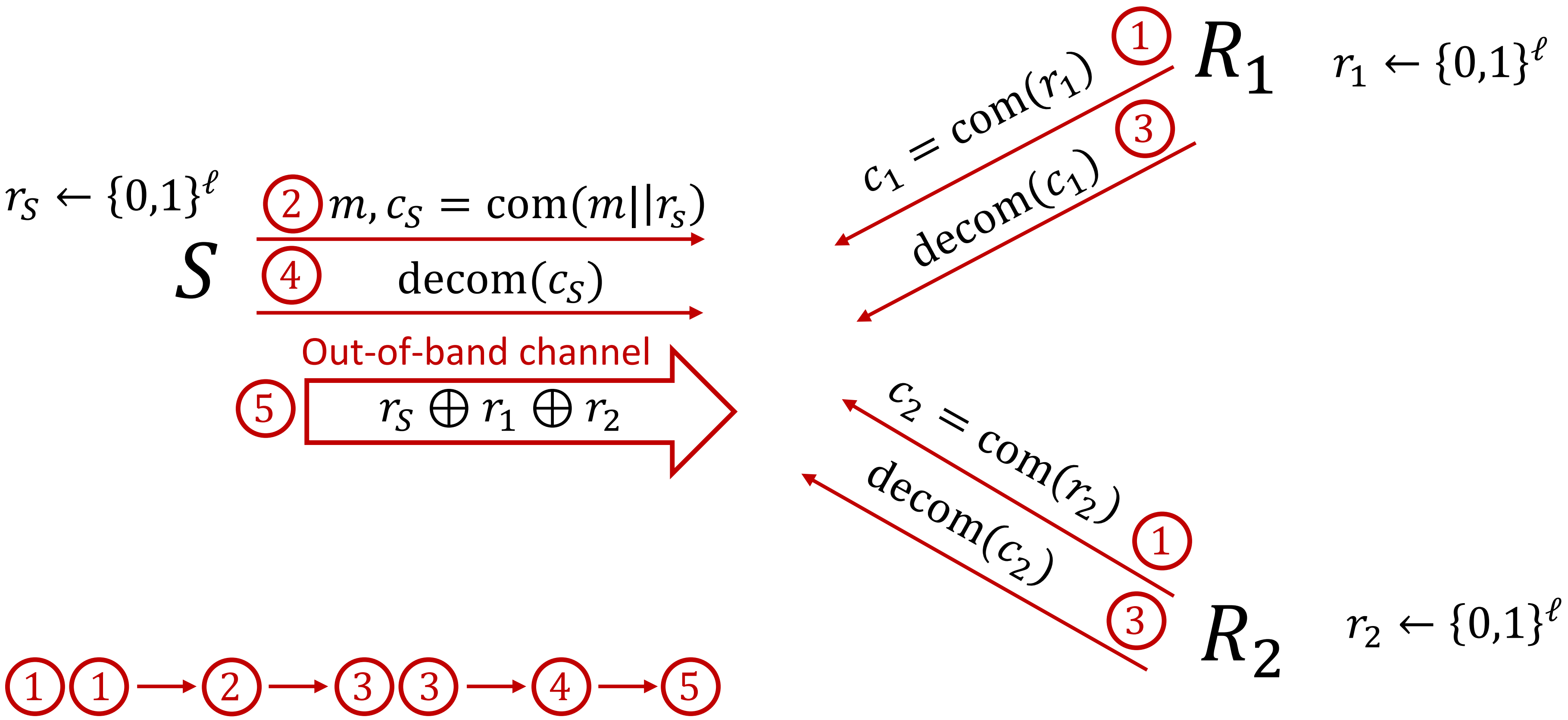
Our First Failure



$$r_S \oplus r_1 \oplus r_2 = \hat{r}_S \oplus r_1 \oplus \hat{r}_2$$

- Solution: Avoid sending r_1 and r_2 in the clear

Our Computationally-Secure Protocol



Our Computationally-Secure Protocol

Theorem:
If $(\text{com}, \text{decom})$ is statistically-binding & concurrent non-malleable, then for any $k, \ell \in \mathbb{N}$ it holds that $\epsilon = k \cdot 2^{-\ell}$

Proof sketch:

- Focus individually on each receiver R_i
- Consider all possible synchronizations of a MitM attack
  - Today: Exemplify 2 notable attacks
- Reduce each one to the security of the commitment scheme
  - Statistical binding or concurrent non-malleability

Attack #1

- S chooses r_S after R_1 decommits

$c_1 = \mathrm{com}(r_1)$

$\mathrm{com}(\widetilde{r_2})$

$r_1 \leftarrow \{0,1\}^\ell$

$\widehat{m}, \mathrm{com}(\widehat{m}||\widehat{r_S})$

S

R_1

$\mathrm{decom}(c_1)$

$r_S \leftarrow \{0,1\}^\ell$

$\mathrm{com}(\widehat{r_1}), \mathrm{com}(\widehat{r_2})$

$c_S = \mathrm{com}(m||r_S)$

- R_1 accepts $\widehat{m}$ if and only if $r_s \oplus \widehat{r_1} \oplus \widehat{r_2} = \widehat{r_S} \oplus r_1 \oplus \widetilde{r_2}$
- Statistical binding implies that, by the time r_s is chosen, all values except for r_s are already determined

$$\Pr_{r_S \leftarrow \{0,1\}^\ell}[r_s = \widehat{r_1} \oplus \widehat{r_2} \oplus \widehat{r_S} \oplus r_1 \oplus \widetilde{r_2}] = 2^{-\ell}$$

Attack #2

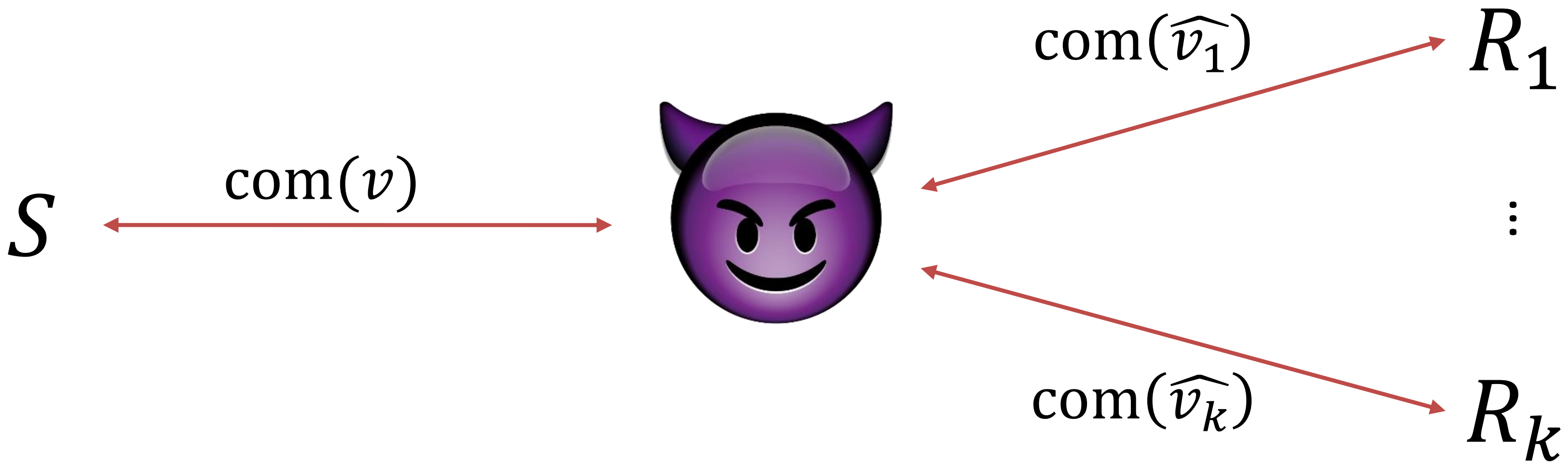
- S chooses r_S before R_1 decommits

- Fix "worst-case" $r_1, \hat{r}_1$ and $\hat{r}_2$
- Attacker gets $\mathrm{com}(m||r_S)$ and needs to output $\mathrm{com}(\tilde{r}_2)$ and $\mathrm{com}(\hat{m}||\hat{r}_S)$ such that $r_s \oplus \hat{r}_1 \oplus \hat{r}_2 = \hat{r}_S \oplus r_1 \oplus \tilde{r}_2$
- Concurrent non-malleability implies that either $m = \hat{m}$ or

$$\Pr[r_s \oplus \hat{r}_1 \oplus \hat{r}_2 = \hat{r}_S \oplus r_1 \oplus \tilde{r}_2] = 2^{-\ell} + \nu(\lambda)$$

Concurrent Non-Malleable Commitments

- Infeasible to “non-trivially correlate” concurrent executions



- Constant-round schemes from any one-way function [PR05, PR06, LPV08, LP11, Goy11, GRRV14, GPR16, COSV17, …]

- Simple, efficient and non-interactive in the random-oracle model

$$\mathrm{com}(v; r) = \mathrm{Hash}(v||r)$$

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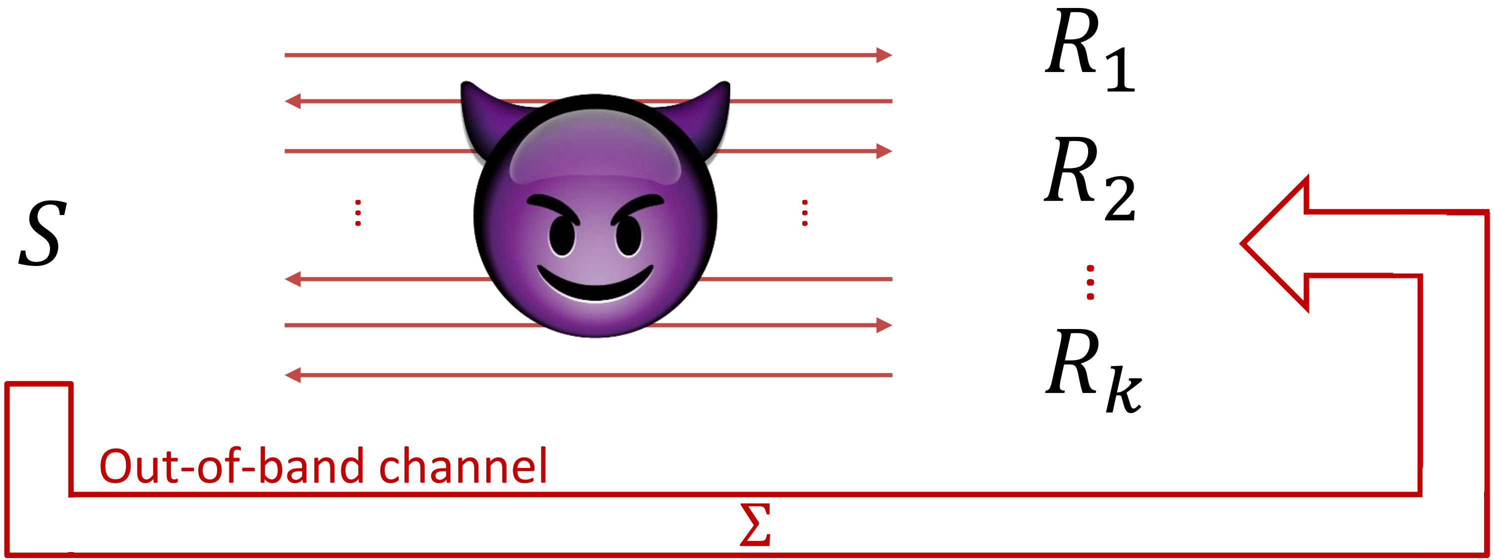
- The naïve protocol
- Our protocols & lower bounds

	Protocols	Lower Bounds
Computational Security	$\log(1/\epsilon) + \log k$	$\log(1/\epsilon) + \log k - O(1)$
Statistical Security	$(k+1) \cdot \big(\log(1/\epsilon) + \log k + O(1)\big)$	$(k+1) \cdot \log(1/\epsilon) - k$

Our Statistical Lower Bound



- Denote by Σ the out-of-band value in an honest execution with a random m
- During any execution Σ's Shannon entropy decreases from $H(\Sigma)$ to 0
- **Intuition [NSS06]:** Each party must "independently reduce" at least $\log(1/\epsilon)$ bits from $H(\Sigma)$

$k = 1$ $H(\Sigma) \geq (k+1) \cdot \log(1/\epsilon)$

Our Statistical Lower Bound

- We present $k+1$ attacks that succeed with probabilities $\epsilon_0, \dots, \epsilon_k$ such that

$$2^{-H(\Sigma)-k} \leq \prod_{i=0}^{k} \epsilon_i$$

- The security of the protocol guarantees that

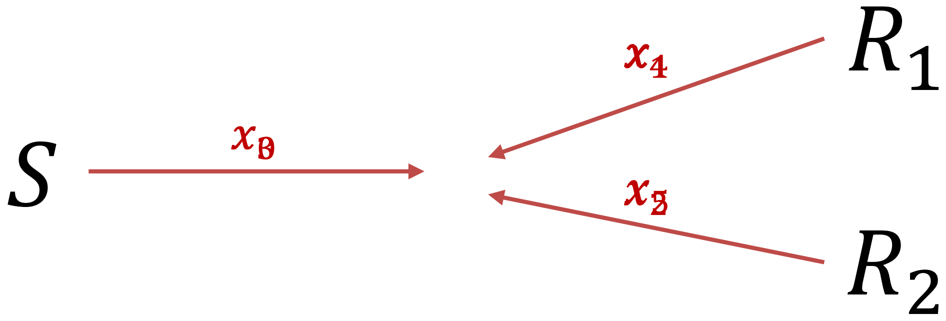
$$\prod_{i=0}^{k} \epsilon_i \leq \epsilon^{k+1}$$

$$\Downarrow$$

$$H(\Sigma) \geq (k+1) \cdot \log(1/\epsilon) - k$$

Protocol Structure

- Assume that the protocol has t rounds over the insecure channel
- In each round i a single party is "active" and sends messages
  - If $i \equiv 0 \bmod (k+1)$ then S is active
  - Otherwise, $R_{i \bmod (k+1)}$ is active
- Denote by x_i the vector of messages sent in round i



Understanding $H(\Sigma)$

- Random variables $M, X_0, \ldots, X_{t-1}, \Sigma$
- Split $H(\Sigma)$ according to the marginal contribution of each round:

$$H(\Sigma) = H(\Sigma) - H(\Sigma|M, X_0) + H(\Sigma|M, X_0) - H(\Sigma|M, X_0, X_1) + H(\Sigma|M, X_0, X_1)$$

$$- \ \ldots - H(\Sigma|M, X_0, \ldots, X_{t-1}) + H(\Sigma|M, X_0, \ldots, X_{t-1})$$

$$= I(\Sigma; M, X_0) + \sum_{j \in [t]: j \equiv 0 \bmod (k+1)} I(\Sigma; X_j | M, X_0, \ldots, X_{j-1})$$

$$+ \sum_{i \in [k]} \sum_{j \equiv i \bmod (k+1)} I(\Sigma; X_j | M, X_0, \ldots, X_{j-1})$$

$$+ H(\Sigma|M, X_0, \ldots, X_{t-1})$$

Entropy reduction by S

Entropy reduction by R_i

Understanding $H(\Sigma)$

Lemma 1:
There exists a man-in-the-middle attacker that succeeds with probability

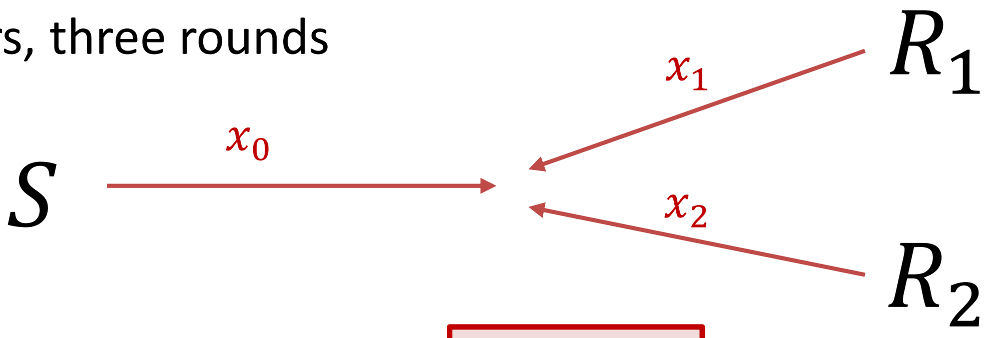
$$\epsilon_0 \geq 2^{-\left(I(\Sigma; M, X_0) + \sum_{j \equiv 0 \bmod (k+1)} I\left(\Sigma; X_j \middle| M, X_0, \ldots, X_{j-1}\right) + H(\Sigma | M, X_0, \ldots, X_{t-1})\right)}$$

Lemma 2:
For every $i \in [k]$ there exists a man-in-the-middle attacker that succeeds with probability

$$\epsilon_i \geq 2^{-\sum_{j \equiv i \bmod (k+1)} I\left(\Sigma; X_j \middle| M, X_0, \ldots, X_{j-1}\right)}$$

Simplified Case

- Two receivers, three rounds



$$H(\Sigma) = I(\Sigma; M, X_0) + I(\Sigma; X_1 | M, X_0) + I(\Sigma; X_2 | M, X_0, X_1) + H(\Sigma | M, X_0, X_1, X_2)$$

Entropy reduction by S

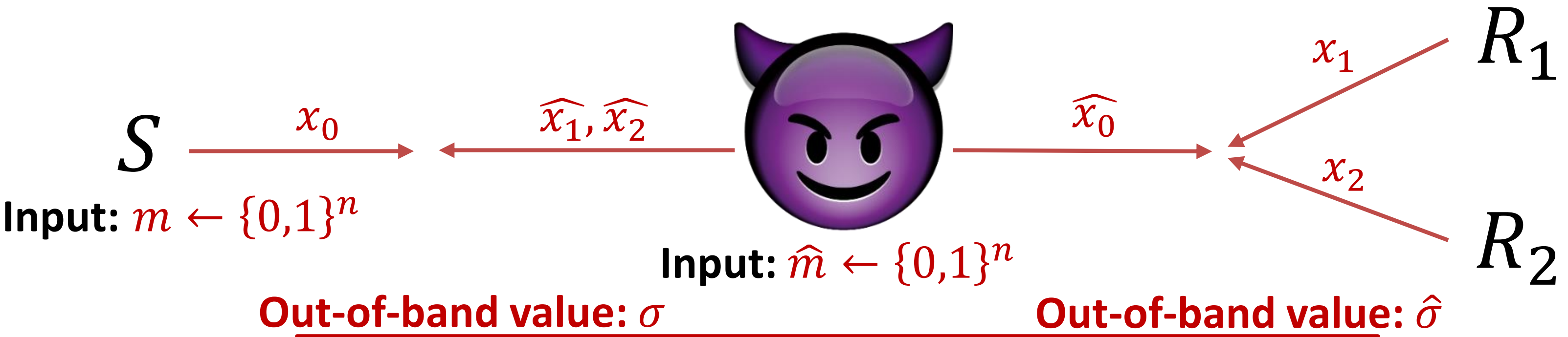
Entropy reduction by R_1

Entropy reduction by R_2

Lemma 1 - Simplified Case

The attack:

- Run an honest execution with (R_1, R_2) while simulating S on a random $\hat{m}$
- Run an execution with S on a random m while simulating (R_1, R_2)
  - However, instead of sampling $(\widehat{x_1}, \widehat{x_2})$ from the conditional distribution $(X_1, X_2)|m, x_0$, sample them from $(X_1, X_2)|m, x_0, \hat{\sigma}$
- Forward σ to (R_1, R_2)



- If $\sigma = \hat{\sigma}$ then $\Pr[\sigma = \hat{\sigma}] \geq 2^{-(I(\Sigma; M, X_0) + H(\Sigma | M, X_0, X_1, X_2))}$

Summary

A framework modeling out-of-band authentication in the group setting

Tight bounds for out-of-band authentication in the group setting

	Protocols	Lower Bounds
Computational Security	$\log(1/\epsilon) + \log k$	$\log(1/\epsilon) + \log k - O(1)$
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Thank You!