Practical Distributed Authorization

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Two day course at the 2016 International school on Foundations of Security Analysis and Design, Bertinoro, Italy (Aug. 29 - Sep. 3)

Plan for today

- Vanadium access control policies
  - Key features
  - Algorithms and formalization
- Privacy, discovery and authentication for Vanadium and IoT
  - Problem statement
  - Review of cryptographic techniques
  - Protocol design, implementation, and benchmarks

Access Control Policies in Vanadium

Joint work with Martin Abadi, Mike Burrows, Himabindu Pucha, Adam Sadowsky, and Asim Shankar

Recap: Vanadium authorization model

Principal and Blessings

Principal is a unique public/private key pair with human-readable names bound to it

All communication is encrypted & mutually authenticated

Forward-secrecy safe protocol, client and service identity privacy

Authorization is based on blessing names

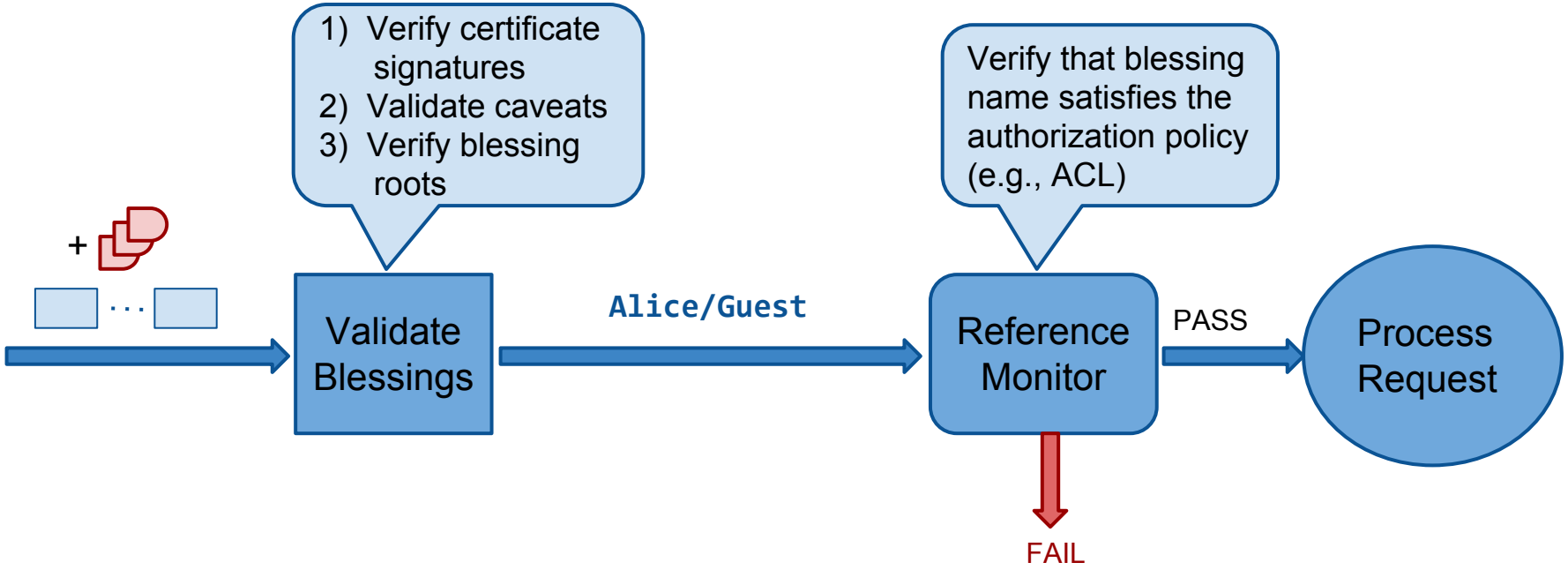
Principals authenticated and authorized based on their blessing names

Fine-grained delegation and audit

Principals can bind an extension of their blessings to another principal under caveats

Recap: Vanadium authorization model

Authorization policies are based on blessing names.



Plan

- Overview of access control policies
  - Distributed groups
  - Blessing patterns
  - Positive and negative constraints
- Formal semantics of access control
- Algorithms, implementation and trade-offs

Access control policies

Explicitly specify set of authorized blessings

Label	**Policy**
Photos	**Allow**: Alice, Alice/TV
Movies	**Allow**: Alice/Tablet

Access control policies

Explicitly specify set of authorized blessings

Label	Policy
Photos	**Allow**: Alice, Alice/TV
Movies	**Allow**: Alice/Tablet

Access control list (ACL)

This is the object of study for this lecture

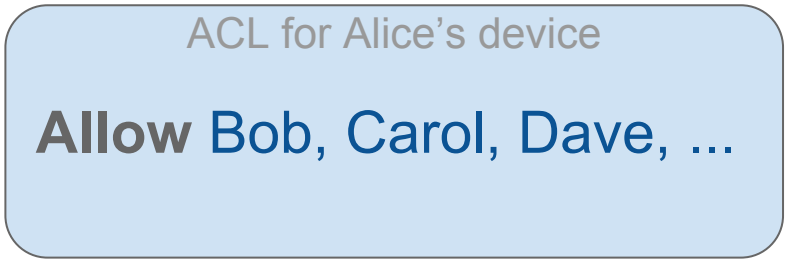
Access control lists

Enumerate the set of authorized blessing names

How does Alice grant access to all her friends?

Access control lists

Enumerate blessing names of all friends



But, this is too cumbersome especially if it has to be done for several ACLs

Groups

Indirect through a group specifying Alice's friends

ACL for Alice's device

Allow $Friends_G$

$Friends_G$ = Bob, Carol, Dave, ...

Groups

Groups may contain blessing names with multiple components

ACL for Alice's device

Allow Friends_G

Friends_G = Bob, Carol, Dave, **Carol/Friends/Eve**, ...

Groups

The group can be modified independent of the ACL

ACL for Alice's device

Allow $Friends_G$

$Friends_G$ = Bob, Carol, Dave, ~~**Carol/Friends/Eve**~~, ...

Nested groups

Groups may depend on other groups

ACL for Alice's device

Allow $Friends_G$

$Friends_G$ = Bob, Carol, Dave, $BobFriends_G$, ...

$BobFriends_G$ = Mike, James, ...

Nested groups

Groups may depend on other groups

ACL for Alice's device

Allow $Friends_G$

$Friends_G$ = Bob, Carol, Dave, $BobFriends_G$, ...

$BobFriends_G$ = Mike, James, ...

Challenge: Group definitions may be spread across multiple administrative domains

Blessing patterns

Group names can be used within blessing names to form ***blessing patterns***

ACL for Alice's device

Allow $Friends_G$/Phone

$Friends_G$ = Bob, Carol, ...

$Friends_G$/Phone is matched by Bob/Phone, Carol/Phone, etc.

Blessing patterns

Group names can be used within blessing names to form ***blessing patterns***

ACL for Alice's device

Allow $\text{Friends}_G/\text{Devices}_G$

Friends_G = Bob, Carol, ...

Devices_G = Phone, Tablet

$\text{Friends}_G/\text{Devices}_G$ is matched by Bob/Phone, Carol/Tablet, etc.

Negative entries

Deny access to certain blessing names

ACL for Alice's device

Allow $Friends_G$

Deny Carol

$Friends_G$ = Bob, Carol, ...

Negative entries

Deny access to entire groups

ACL for Alice's device

Allow Friends_G

Deny $\textbf{Enemies}_G$

Friends_G = Bob, Carol, ...

$\textbf{Enemies}_G$ = Carol, Mike, ...

Negative entries

Deny access to entire groups

ACL for Alice's device

Allow Friends_G

Deny $\textbf{Enemies}_G$

Friends_G = Bob, Carol, ...

$\textbf{Enemies}_G$ = Carol, Mike, ...

Challenge: Checking non-membership in a group

Blessing name extensions

ACL for Alice's device

Allow Alice, Bob

Deny Carol

Are extensions of Alice (e.g., Alice/Guest) allowed?

Are extensions of Carol (e.g., Carol/Phone) denied?

Blessing name extensions

ACL for Alice's device

Allow Alice, Bob

Deny Carol

Are extensions of Alice (e.g., Alice/Guest) allowed?

Yes

Are extensions of Carol (e.g., Carol/Phone) denied?

Yes

But the reasons are very different

Extensions of allowed names

ACL for Alice's device

Allow Alice, Bob

Deny Carol

Extensions of allowed blessing names are allowed for convenience

Simply say **Allow** Alice to allow access to all of Alice's delegates (e.g., Alice/Phone, Alice/Guest, etc.)

Stricter policy can be encoded with Alice/**$** that only matches Alice

Extensions of denied names

ACL for Alice's device

Allow Alice, Bob

Deny Carol

Extensions of denied blessing names are denied for security reasons

A principal with blessing Carol can easily extend it (say to Carol/Phone)

Thus, denying Carol must also imply denying all extensions of Carol

Recap of ACL features

- **Allow** and **Deny** clauses of blessing patterns
- Blessing patterns can contain group names
- Distributed group definitions
- Liberal matching on blessing pattern extensions

Fully decentralized with no overseeing authority

Need for formalization

Let $Friends_G$ = Bob, Carol

Which of the following ACLs grant access to Bob/Phone?

ACL1

Allow $Friends_G$

Deny $Friends_G$

ACL2

Allow $Friends_G$

Deny $Friends_G$/ Phone

ACL3

Allow $Friends_G$/ Phone

Deny $Friends_G$

Need for formalization

Let $Friends_G$ = Bob, Carol

Which of the following ACLs grant access to Bob/Phone?

ACL1	ACL2	ACL3
Allow $Friends_G$	**Allow** $Friends_G$	**Allow** $Friends_G$/ Phone
Deny $Friends_G$	**Deny** $Friends_G$/ Phone	**Deny** $Friends_G$

We must formally define the semantics of ACLs

Formalizing ACL semantics

Syntax

$$
\begin{array}{rcll}
bn & ::= & n & \text{blessing names} \\
 & | & n \;/\; bn & \\
p & ::= & n & \text{blessing patterns} \\
 & | & g & \\
 & | & n \;/\; p & \\
 & | & g \;/\; p & \\
P & ::= & \texttt{empty} & \text{list of blessing patterns} \\
 & | & P : p & \\
A & ::= & \texttt{Allow}\ P\ \ \texttt{Deny}\ P & \text{ACL}
\end{array}
$$

Semantics

Objective: Define a predicate **IsAuthorized(bn, A)** that checks whether a blessing name bn is allowed by the ACL A

Plan

- Assume a semantics ρ for groups
  ρ maps a group name to the set of member blessing names
- Define “Meaning” of a blessing pattern in terms of ρ
  Meaning maps a blessing pattern to the set of blessing names matched by it
- Use Meaning to define IsAuthorized

Meaning of blessing patterns

$$
\begin{aligned}
&\text{Meaning}_\rho(p) ::= \\
&\quad \texttt{case } p \texttt{ of} \\
&\qquad n \quad : \{n\} \\
&\qquad \mid g \quad : \rho(g) \\
&\qquad \mid n \,/\, p : \{n \,/\, s \mid s \in \text{Meaning}_\rho(p)\} \\
&\qquad \mid g \,/\, p : \{s \,/\, s' \mid s \in \text{Meaning}_\rho(g), s' \in \text{Meaning}_\rho(p)\}
\end{aligned}
$$

If $\rho(\text{Friends}_G)$ = {Bob, Alice/Friend} then

Meaning(Friends_G / phone) = { Bob/Phone, Alice/Friend/Phone}

Prefix matching (□)

bn1 □ **bn2** if and only if bn1 == bn2 OR bn1 is an extension of bn2

e.g., Alice □ Alice/Phone is True

Ali □ Alice /Phone is False

IsAuthorized

$$\text{IsAuthorized}(bn, \textbf{Allow } P_A \textbf{ Deny } P_D) :=$$

$$\exists\ bn_1 \in \text{Meaning}_{\rho}(P_A).\ bn_1 \square bn$$

$$\wedge \neg\ \exists\ bn_1 \in \text{Meaning}_{\rho}(P_D).\ bn_1 \square bn$$

IsAuthorized

IsAuthorized(bn, **Allow** P_A **Deny** P_D) :=

$\exists\ bn_1 \in Meaning_{\rho}(P_A).\ bn_1 \sqsubset bn$

$\wedge \neg\ \exists\ bn_1 \in Meaning_{\rho}(P_D).\ bn_1 \sqsubset bn$

MUST be an extension of **some** blessing name matched by Allowed pattern

IsAuthorized

IsAuthorized(bn, **Allow** P_A **Deny** P_D) :=

$$\exists\ bn_1 \in Meaning_{\rho}(P_A).\ bn_1 \sqsubseteq bn$$

$$\wedge\ \neg\ \exists\ bn_1 \in Meaning_{\rho}(P_D).\ bn_1 \sqsubseteq bn$$

MUST be an extension of **some** blessing name matched by Allowed pattern

MUST NOT be an extension of **any** blessing name matched by Denied pattern

Semantics of Groups

How do we define ρ?

Challenges

- Distributed group definitions
- Membership list must be held private (as much as possible)
- Cyclic dependencies

  $AliceFriends_G$ = Carol, $BobFriends_G$

  $BobFriends_G$ = Mike, $AliceFriends_G$
- No central overseeing authority

Observation: Group definitions induce formal grammars

ACL

Allow $\text{AliceFriends}_G/\text{Devices}_G$

Deny AliceEnemies_G

Groups

AliceFriends_G = Carol, BobFriends_G

BobFriends_G = Mike, AliceFriends_G

Devices_G = Phone, Tablet

AliceEnemies_G = Carol, James

Group names are non-terminals and group definitions are productions

$\rho(\text{AliceFriends}_G)$ is the language induced by AliceFriends_G

Checking membership in $\rho(\text{AliceFriends}_G)$ is akin to parsing

Distributed grammars

What if some group definitions (grammar productions) are unreachable?

Conservatively approximate => Define two semantics ρ⇩ and ρ⇧

- **ρ⇩ (rho-under)**: Map unreachable groups to empty set
  Used in determining meaning of **Allow** patterns
- **ρ⇧ (rho-over)**: Map unreachable groups to set of all blessing names
  Used in determining meaning of **Deny** patterns

IsAuthorized (approximate)

IsAuthorized(bn, **Allow** P_A **Deny** P_D) :=

$$\exists\ bn_1 \in \text{Meaning}_{\rho\Downarrow}(P_A).\ bn_1 \sqsubseteq bn$$

$$\wedge \neg\ \exists\ bn_1 \in \text{Meaning}_{\rho\Uparrow}(P_D).\ bn_1 \sqsubseteq bn$$

Next step: Design an algorithm for evaluating $\exists\ bn_1 \in \text{Meaning}_{\rho}(P_A).\ bn_1 \sqsubseteq bn$ without expanding the definition of ρ

The “Rest” algorithm for distributed parsing

Parsing problem: Match a blessing name against a blessing pattern
e.g., match Mike/Phone against AliceFriends_G/Devices_G

Idea: Distributed top-down parsing

- Query a group g: what part of the blessing name bn can g consume and what remains (rest)?
  e.g. , **Rest**(Mike/Phone, AliceFriends_G) = Phone
- Recursively make queries on the “rest” to other groups
- Conservative semantics for unreachable groups

Example

ACL

Allow $\text{AliceFriends}_G/\text{Devices}_G$

Deny AliceEnemies_G

Groups

AliceFriends_G = Carol, BobFriends_G

BobFriends_G = Mike, AliceFriends_G

Devices_G = Phone, Tablet

AliceEnemies_G = Carol, James

Check whether Mike/Phone is authorized

Reference Monitor

Example

ACL

Allow $AliceFriends_G/Devices_G$

Deny $AliceEnemies_G$

Groups

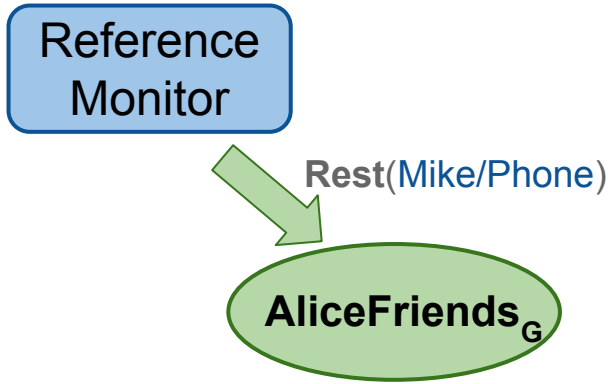
$AliceFriends_G$ = Carol, $BobFriends_G$

$BobFriends_G$ = Mike, $AliceFriends_G$

$Devices_G$ = Phone, Tablet

$AliceEnemies_G$ = Carol, James

Check whether Mike/Phone is authorized



Example

ACL

Allow $AliceFriends_G/Devices_G$

Deny $AliceEnemies_G$

Groups

$AliceFriends_G$ = Carol, $BobFriends_G$

$BobFriends_G$ = Mike, $AliceFriends_G$

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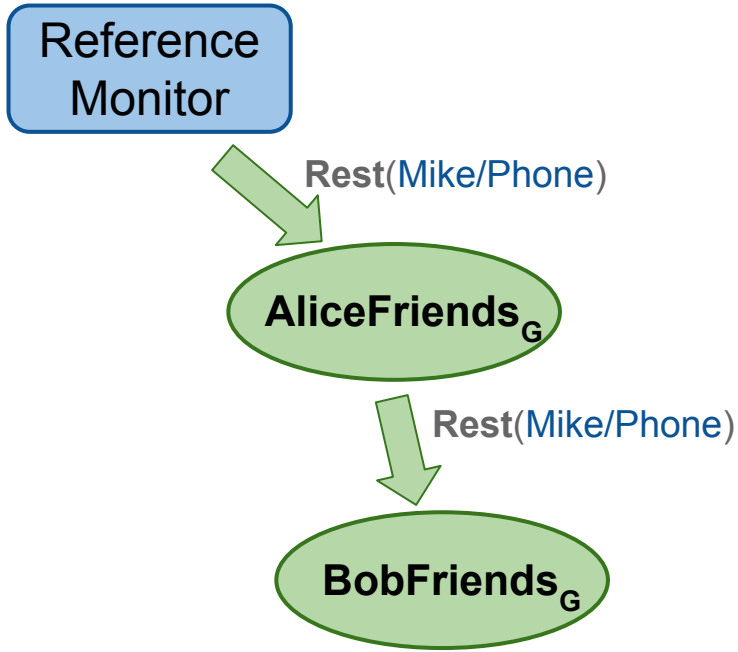
Check whether Mike/Phone is authorized



Example

ACL

Allow $AliceFriends_G/Devices_G$

Deny $AliceEnemies_G$

Groups

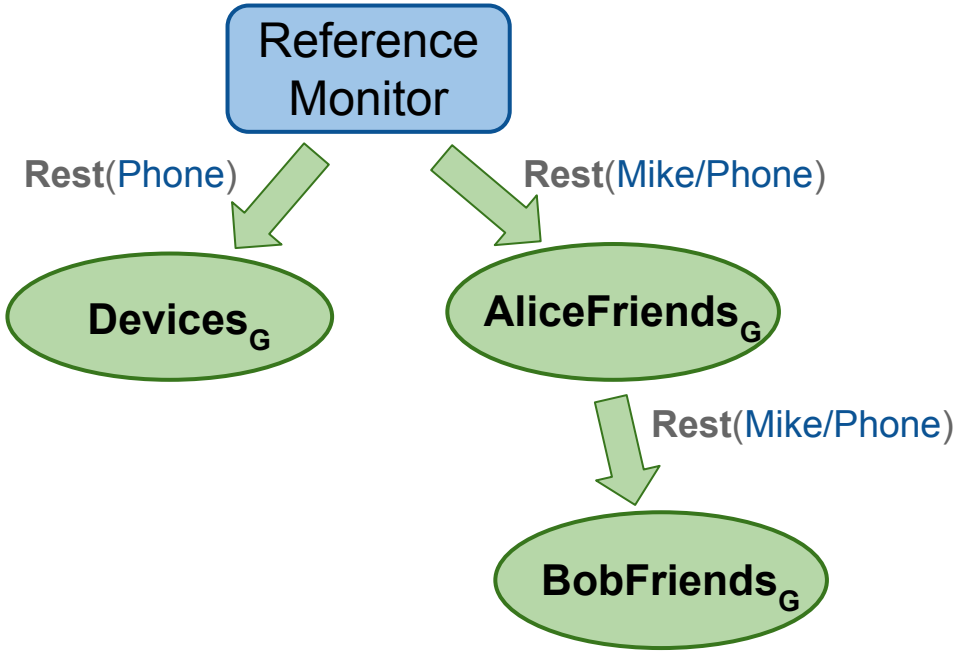
$AliceFriends_G$ = Carol, $BobFriends_G$

$BobFriends_G$ = Mike, $AliceFriends_G$

$Devices_G$ = Phone, Tablet

$AliceEnemies_G$ = Carol, James

Check whether Mike/Phone is authorized



Trade-offs

- Privacy
  - Reference monitor still reveals entire blessing name to group servers and group servers reveal at least part of blessing name that matches
  - **Open problem:** Secure multiparty parsing
- Communication costs
  - Each recursive call results in network communication
  - Left recursive definitions are a problem for top-down parsing
  - Implementations would likely operate under a communication budget
  - Caching vs. mutable group definitions

Perspective

- The combination of local names, distributed groups and deny clauses make access control policies very expressive but complex to validate
- Decentralization makes the problem even for challenging
- Several implementation and design trade-offs make the problem tractable
- Formal methods come to the rescue, yet again!

Distributed Authorization with Distributed Grammars, Abadi et al., PLABS 2014

Privacy, Discovery and Authentication for Internet of Things (IoT)

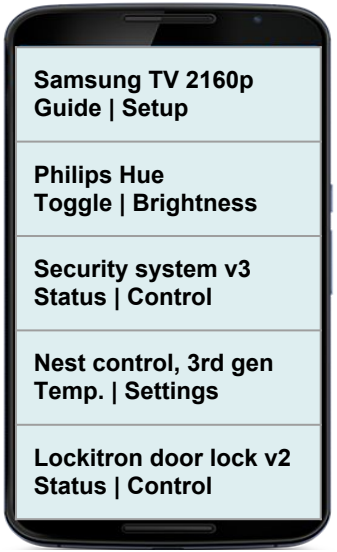
Joint work with
Asim Shankar (Google), David Wu (Stanford University) and
Dan Boneh (Stanford University)

Agenda

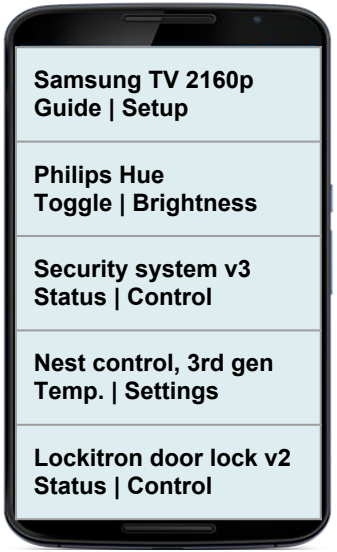
- Two Problems
  - Private service discovery
  - Private mutual authentication
- Solution
  - Identity-Based encryption (IBE)
  - Protocol design, implementation, and benchmarks
- Case study: Apple AirDrop

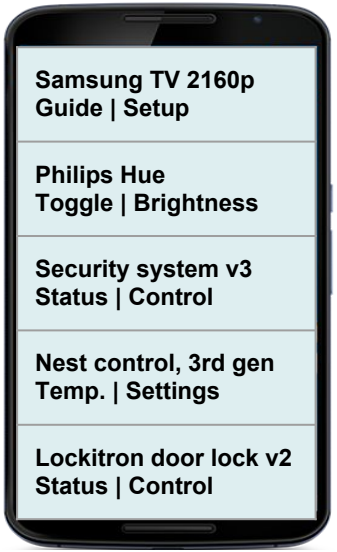
Private Discovery

Alice



Private Discovery





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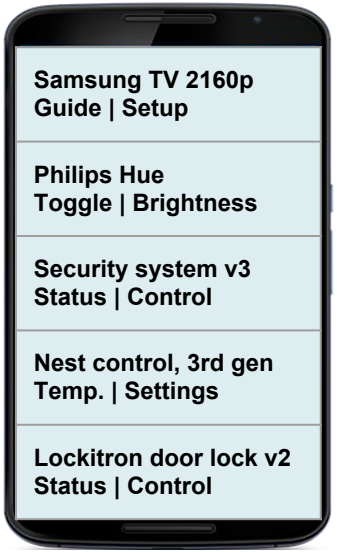

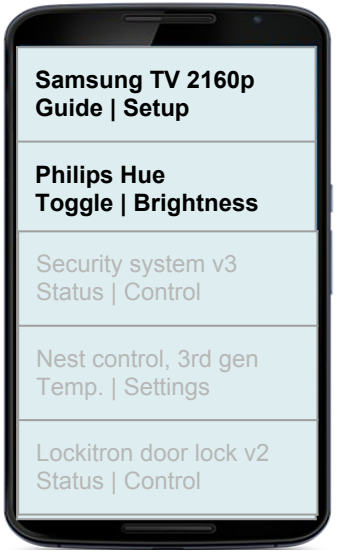

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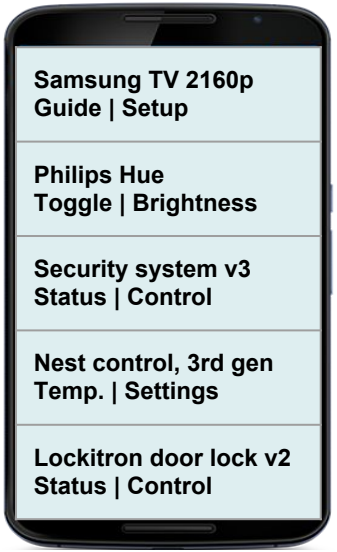

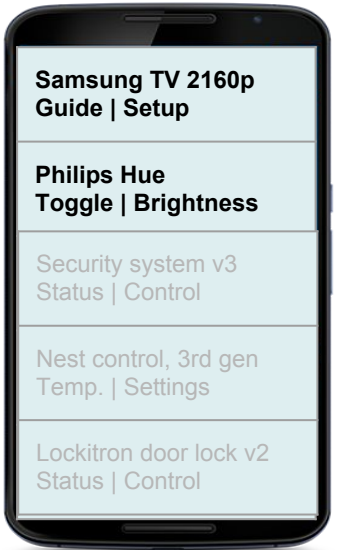

Private Discovery: Services must be discoverable only by authorized parties.

Private discovery is largely unaddressed

No privacy controls in mDNS, Bonjour, and BLE

A recent study of mDNS announcements from 2957 devices in a university campus revealed that 59% devices reveal the device owner name (viewed as a private threat by 92% users)

Advertisements have no authenticity

A rogue device may forge or replay a legitimate service advertisement to determine if a client is interested in the service

Mutual Authentication (SIGMA-I)

Client

Configure

Server

Diffie-Hellman exchange

$\{ \textbf{Blessing}_{\textbf{SecSys}} + \text{Signature}_{\text{SecSys}} \}_k$

$\{ \textbf{Blessing}_{\textbf{Attacker}} + \text{Signature}_{\text{attacker}} \}_k$

Notation

k : key from DH secret

$\{m\}_k$: encryption of m under symmetric key k

Mutual Authentication (SIGMA-I)

Client

Configure

Server

At this point, attacker learns security system's blessings

Attacker may choose to send its blessing or abort.

Diffie-Hellman exchange

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Mutual authentication (SIGMA-I)

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Diffie-Hellman exchange

$\{ \textbf{Blessing}_{SecSys} + Signature_{SecSys} \}_k$

Notation

k : key from DH secret

$\{m\}_k$: encryption of m under symmetric key k

Server's blessing is revealed to *anyone* who communicates with it.
Client's blessing maintains its privacy.

Private mutual authentication

- In most existing mutual authentication protocols (e.g., TLS), one party must “go first”, i.e., reveal its identity first
- But, this is a problem when both the parties are mutually suspicious

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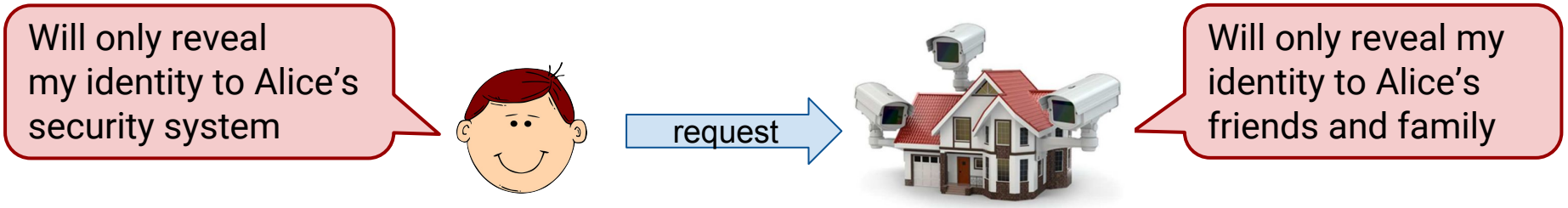
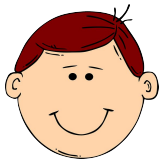


Private mutual authentication

- In most existing mutual authentication protocols (e.g., TLS), one party must “go first”, i.e., reveal its identity first
- But, this is a problem when both the parties are mutually suspicious

Will only reveal my identity to Alice’s security system



request

Will only reveal my identity to Alice’s friends and family

Private mutual authentication: Each end authenticates to the other *if and only if* other end is authorized.

Known approaches

- Use an online trusted third-party to mediate interaction
  - Requires connectivity to third-party
  - Requires trusting the third-party
  - Conflicts with our goal of designing peer-to-peer mechanism
- Out-of-band shared secret between client and server
  - Implies pre-existing relationship between client and server
  - What’s the fun in discovering services you’ve already seen!!

Apple AirDrop

Apple AirDrop

- Peer-to-peer file sharing on iOS (> 7) and OSX (> 10.7) devices
- Uses BLE and Apple’s peer-to-peer WiFi technology (awdl)
- Two modes
  - Everyone (accept files from everyone)
  - Contacts-Only (accept files only from contacts)

AirDrop (contacts-only mode)

Sender

Hash of sender's identity

Receiver

AirDrop (contacts-only mode)

Sender

BLE

Hash of sender's identity

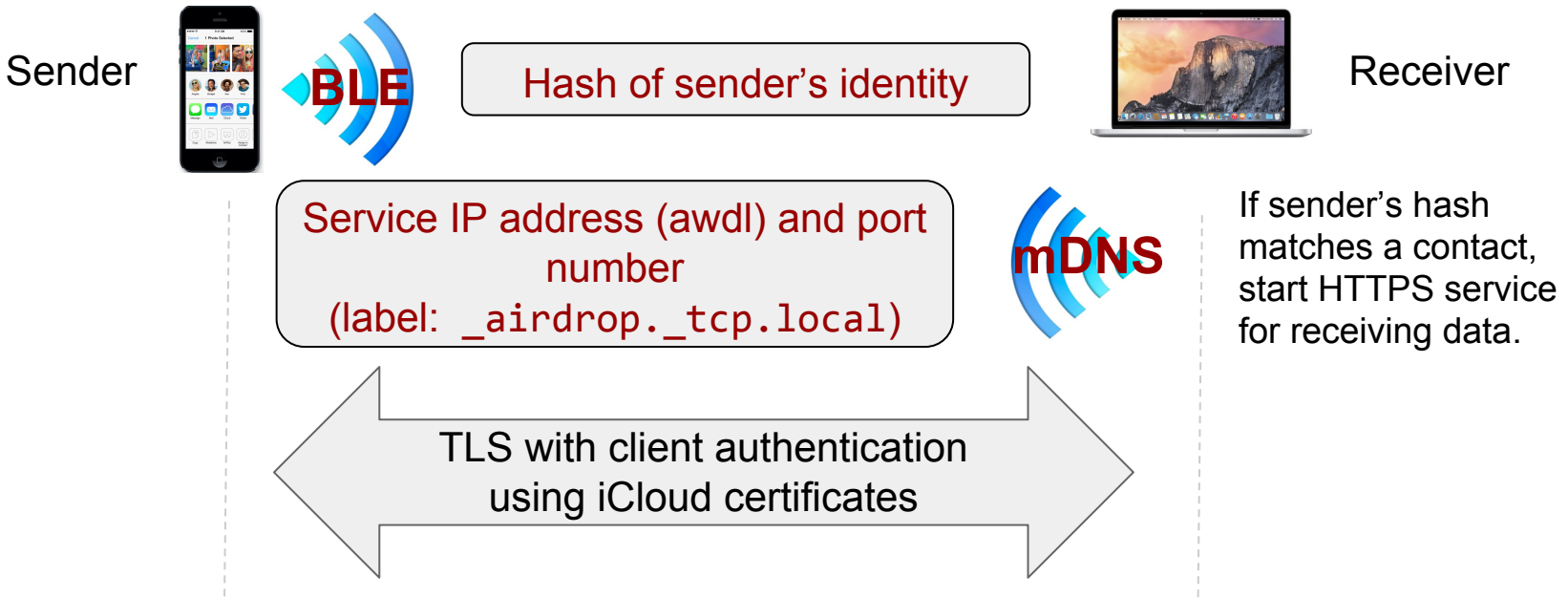
Receiver

Service IP address (awdl) and port number
(label: `_airdrop._tcp.local`)

mDNS

If sender's hash matches a contact, start HTTPS service for receiving data.

AirDrop (contacts-only mode)



AirDrop (contacts-only mode) vulnerabilities

Sender

BLE

Hash of sender's identity

Receiver

Service IP address (awdl) and port number
(label: `_airdrop._tcp.local`)

mDNS

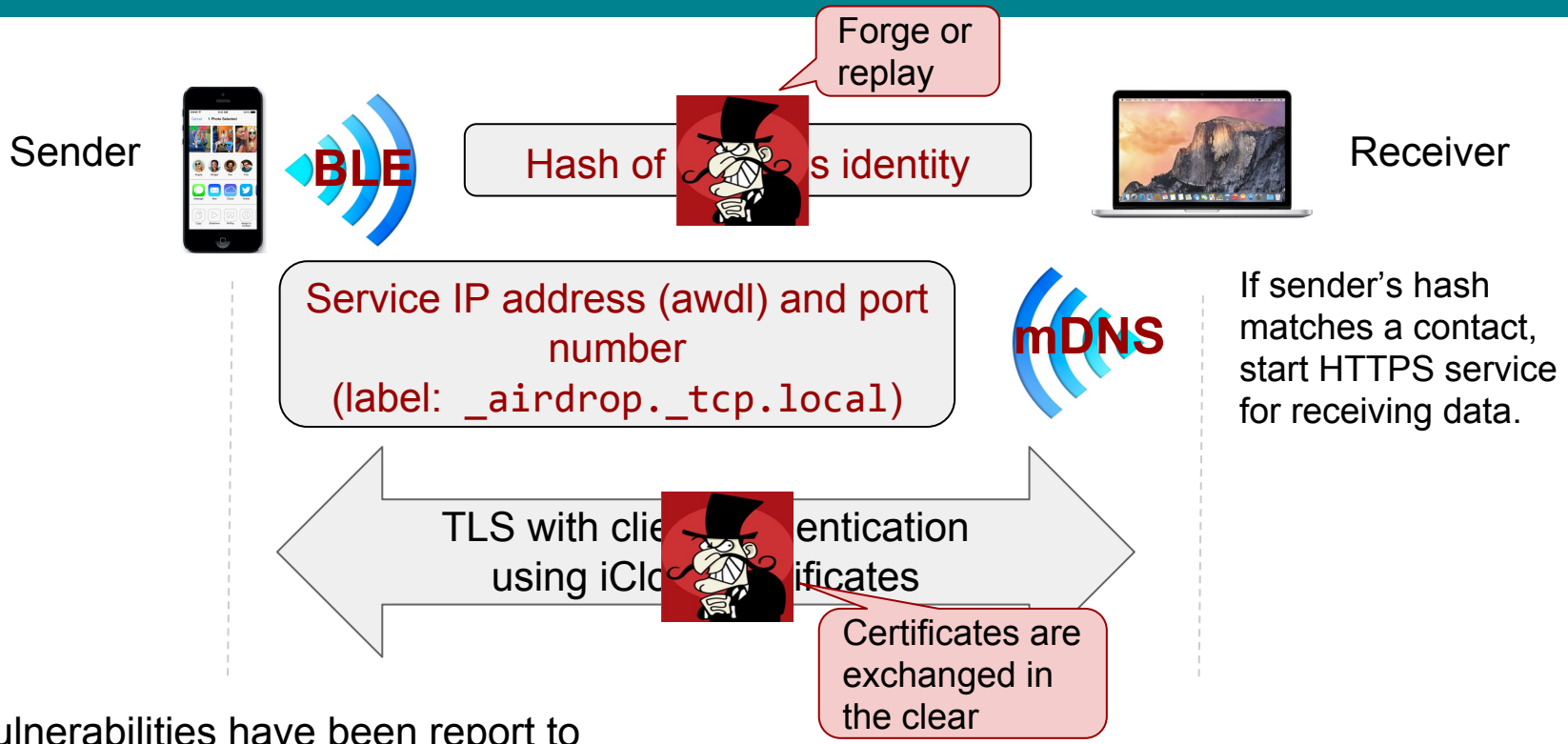
If sender's hash matches a contact, start HTTPS service for receiving data.

TLS with clie entication
using iClo ificates

Certificates are exchanged in the clear

Vulnerabilities have been report to Apple, awaiting response

AirDrop (contacts-only mode) vulnerabilities



Vulnerabilities have been report to Apple, awaiting response

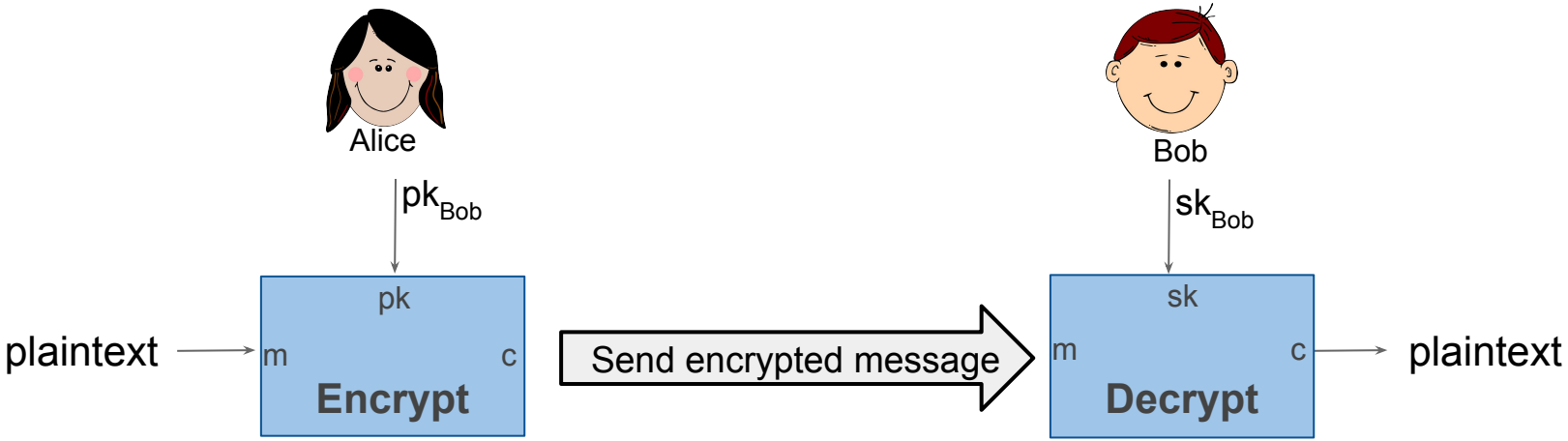
Our design goals

- Mutual privacy
  Protocol participants reveal their identities only to **authorized recipients**
- Authentic advertisements (for service discovery)
  Service advertisements should be unforgeable and authentic
- No dependence on global services during protocol execution
- No out-of-band pairing for participants

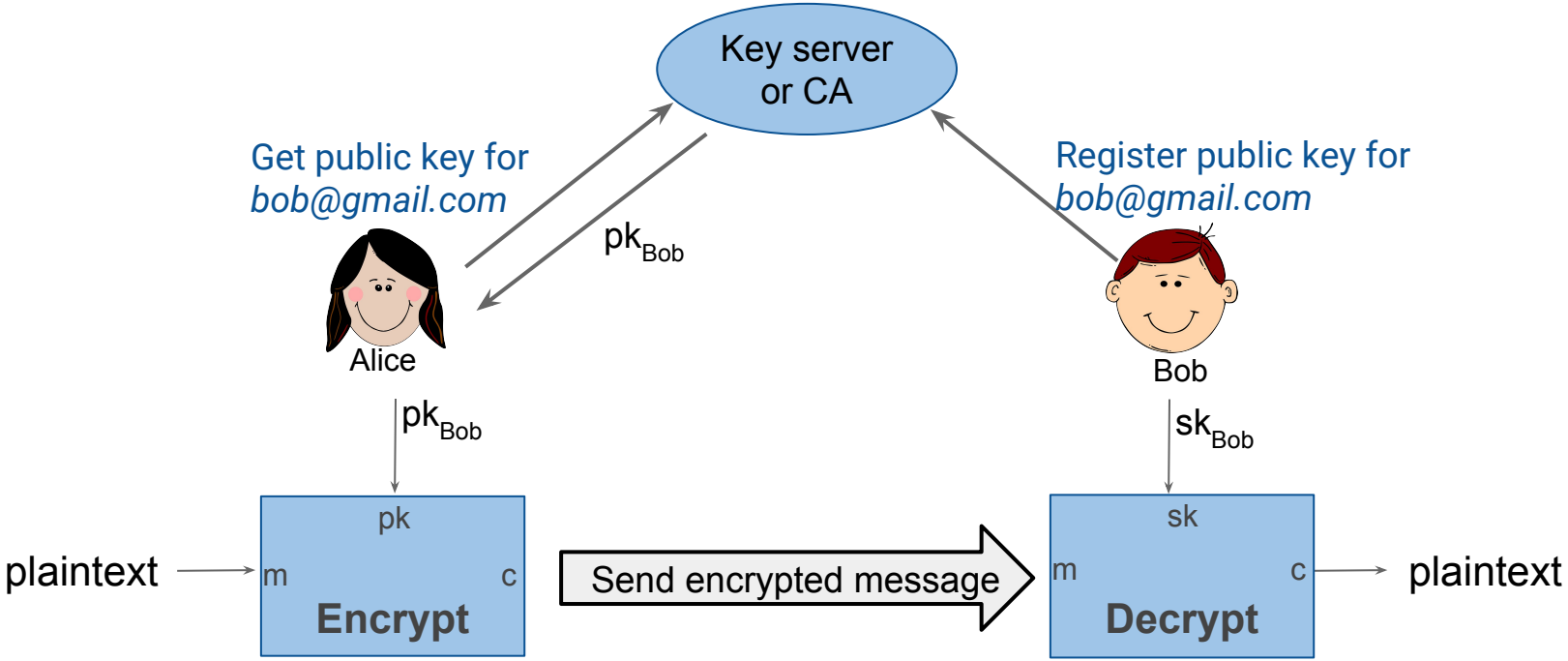
Identity-Based Encryption

Shamir (1984): “*What if your name could be your public key?*”

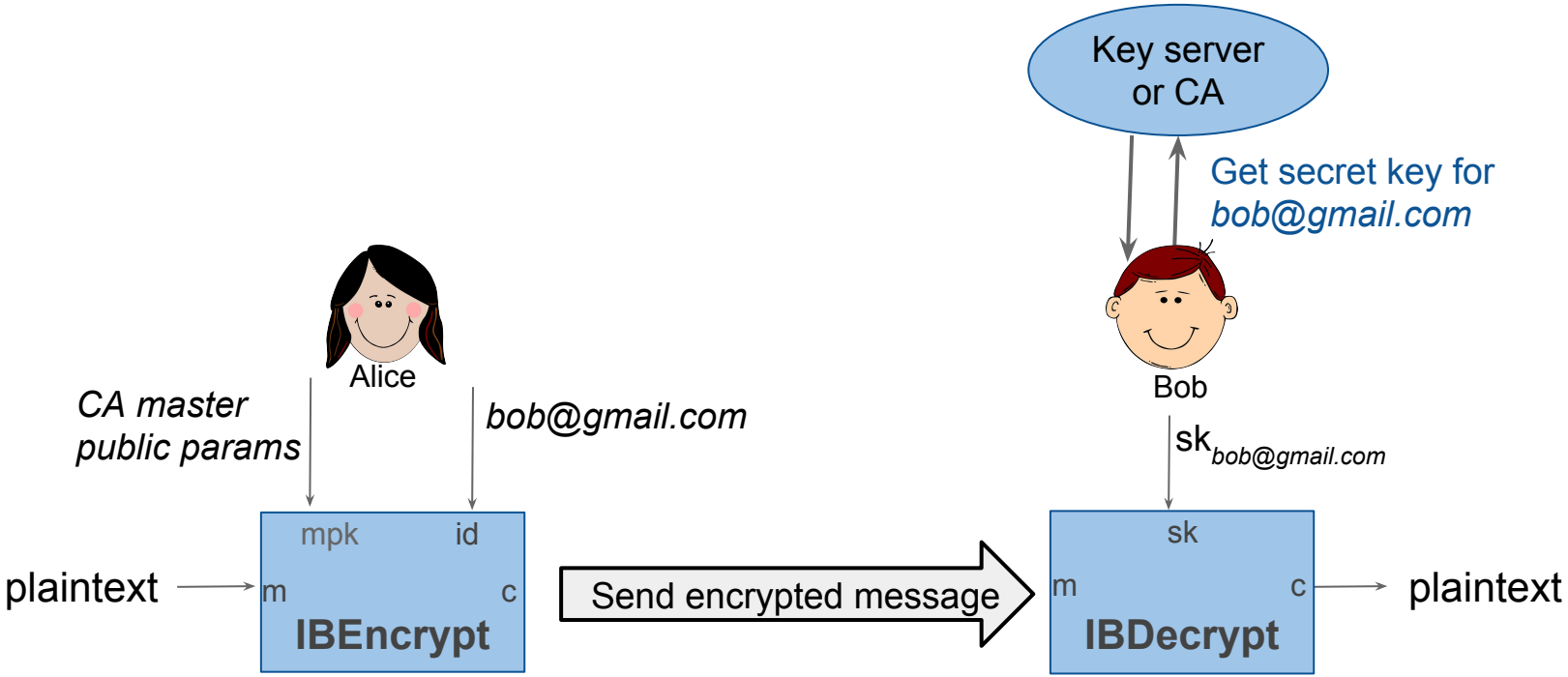
Public-key encryption



Public-key encryption



Identity-based encryption



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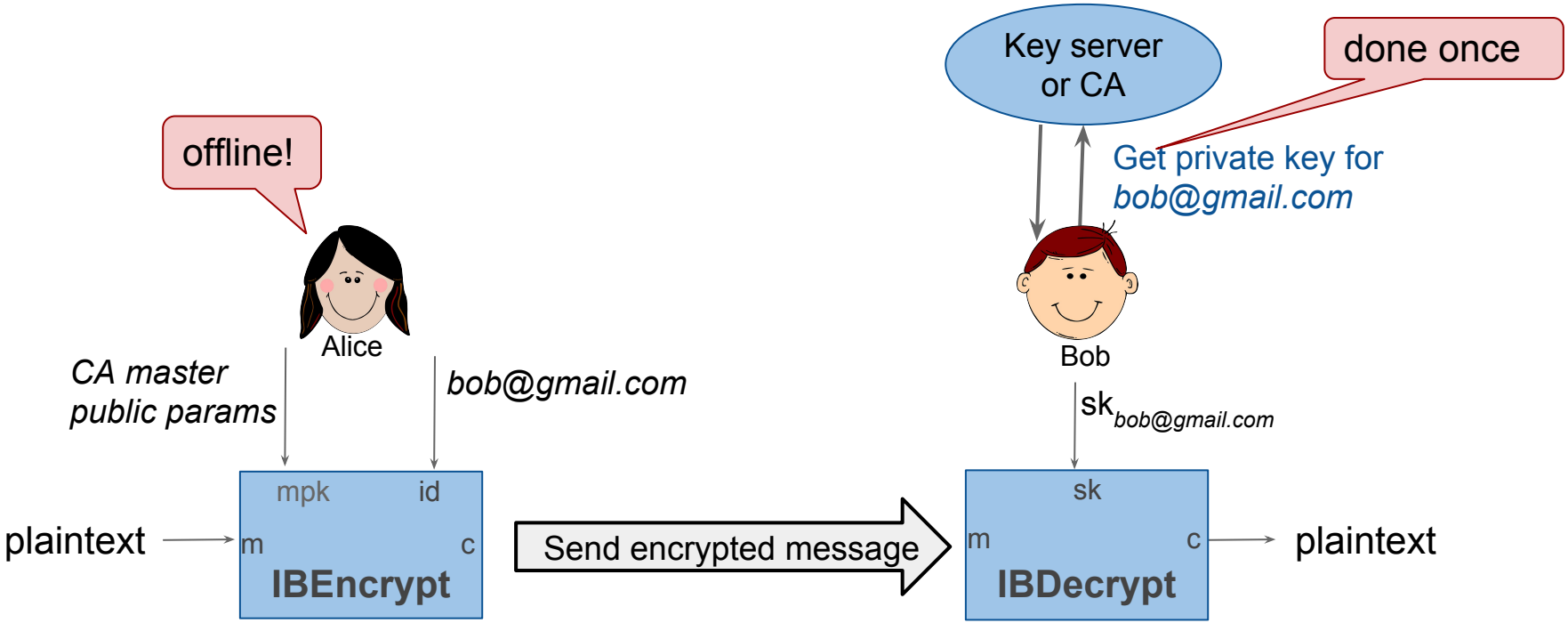
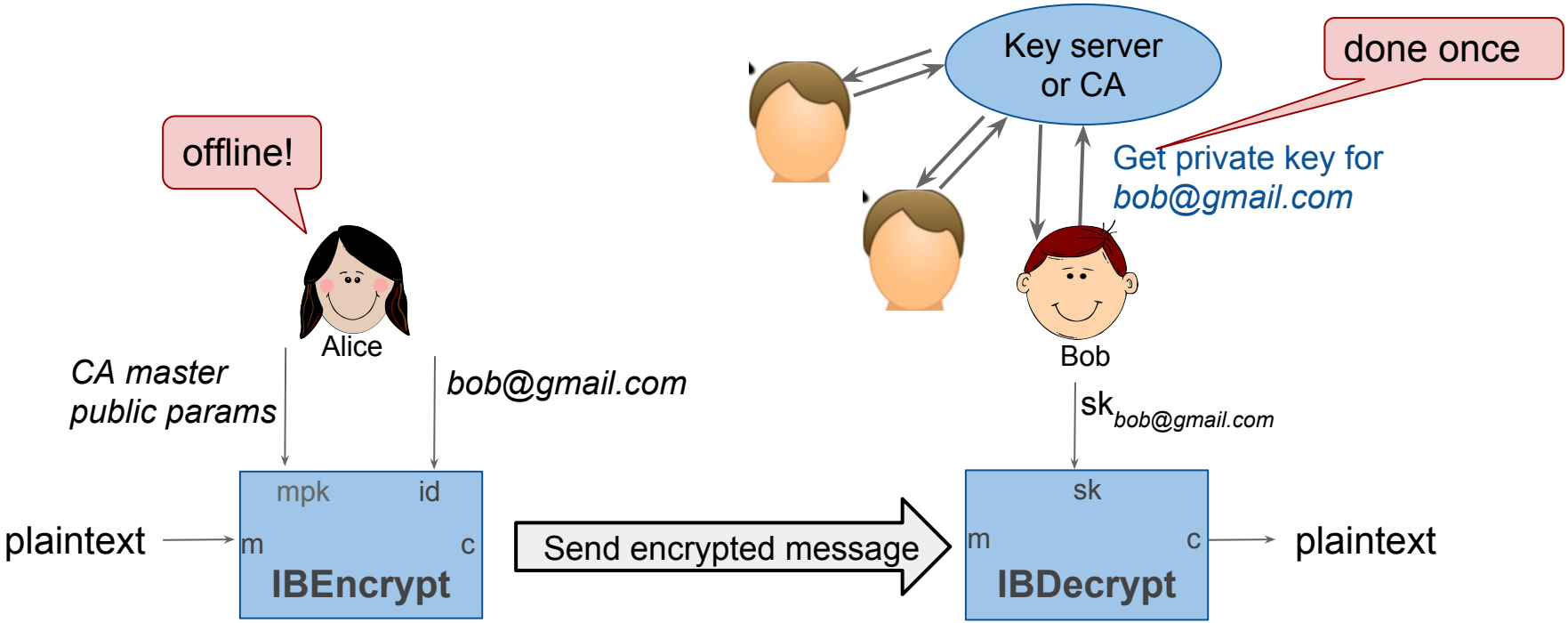


Identity-based encryption



IBE cryptosystem

Operations

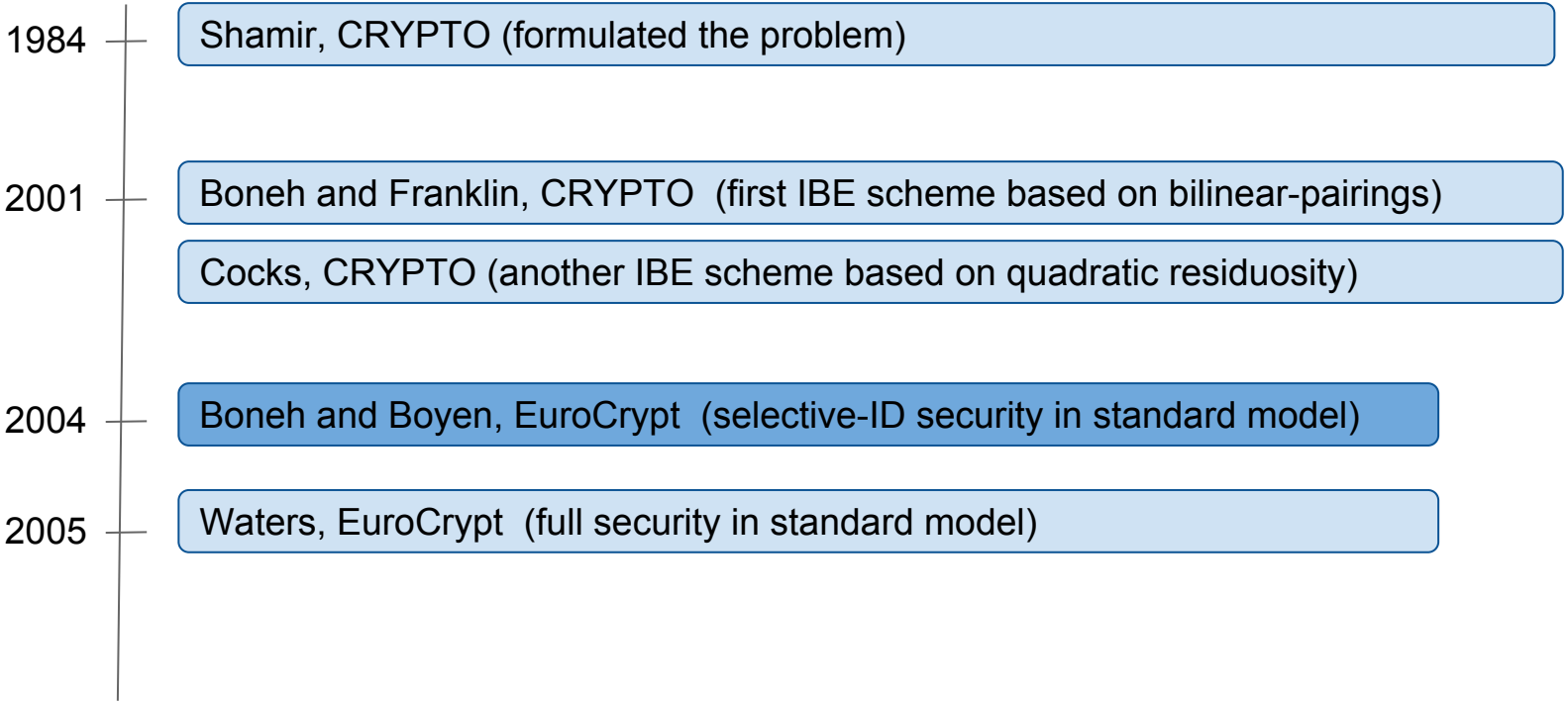
- Encrypt(mpk, ID, ptxt)
- Decrypt(sk_{ID}, ctxt)
- Extract(msk, ID)

Notation

- mpk: master public params (well-known)
- msk: master private key (known to IBE root)
- sk_{ID}: private key for ID
- ptxt : plaintext
- ctxt : ciphertext

$$\forall\ ptxt\ \ \forall\ ID.\ Decrypt(Extract(msk, ID), Encrypt(mpk, ID, ptxt) = ptxt$$

Important IBE results



Private Mutual Authentication

Key Idea

request

Blessing: Alice/Family/Bob
Policy: **Allow** Alice/SecSys

Blessing: Alice/SecSys
Policy: **Allow** Alice/Family

Diffie-Hellman (DH) exchange

$\{ \text{Blessing}_{\text{SecSys}} + \text{Signature}_{\text{SesSys}} \}_k$

$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Notation

k : key from DH secret

$\{m\}_k$:authenticated-encryption of m under key k.

Key idea

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Blessing: Alice/Family/Bob
Policy: **Allow** Alice/SecSys

Blessing: Alice/SecSys
Policy: **Allow** Alice/Family

Bob can read security system's blessings *only if* he satisfies the system's policy.

Bob responds *only if* the security system satisfies his policy.

Diffie-Hellman (DH) exchange

$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} \rangle\!\rangle_{\text{pol}} + \text{Signature}_{\text{SesSys}} \}_k$

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Notation

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Notation

k : key from DH secret

$\{m\}_k$:authenticated-encryption of m under key k.

$\langle\!\langle m \rangle\!\rangle_{\text{pol}}$: encryption of m under policy 'pol'.

How do we build policy-based encryption?

Policy-based encryption

***Problem**: Encrypt a message under an authorization policy so that it can be decrypted only by principals with blessings satisfying the policy*

Policies in Vanadium are blessing prefixes

e.g., Alice/Family is matched by Alice/Family/Bob, Alice/Family/Carol, …

(We simplify and do not consider groups in this work)

We can build prefix-based encryption using IBE [Lewko-Waters '14].

- Encrypt - Use IBEncrypt with prefix as the identity
- Extract - Use IBExtract to obtain a key for each prefix of the blessing

Prefix-based encryption

PrefixEncrypt(mpk, m, “Alice/Family”) returns
IBEncrypt(mpk, m, “Alice/Family”)

PrefixExtract(msk, “Alice/Family/Bob”) returns a vector of private keys extracted for identities

- “Alice”
- “Alice/Family”
- “Alice/Family/Bob”
- “Alice/Family/Bob/$”

Private mutual authentication

request

Blessing: Alice/Family/Bob
Policy: **Allow** Alice/SecSys

Blessing: Alice/SecSys
Policy: **Allow** Alice/Family

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$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} \rangle\!\rangle_{\text{pol}} + \text{Signature}_{\text{SecSys}} \}_k$

$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Notation

k : key from DH secret

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Each end learns its peer's blessing only if it satisfies its peer's authorizaiton policy

Private mutual authentication

request

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Policy: **Allow** Alice/SecSys

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Diffie-Hellman (DH) exchange

$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} \rangle\!\rangle_{\text{pol}} + \text{Signature}_{\text{SecSys}} \}_k$

$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Server overhead: None

Client overhead: One IBE Decryption per handshake

Notation

k : key from DH secret

$\{m\}_k$:authenticated-encryption of m under key k.

$\langle\!\langle m \rangle\!\rangle_{\text{pol}}$: prefix encryption of m under policy 'pol'.

Each end learns its peer's blessing only if it satisfies its peer's authorizaiton policy

Analysis

Theorem: *Protocol satisfies key-exchange security and mutual identity privacy in the Canetti-Krawcyzk model*

Technique may be more generally applicable

- Simply replace server's blessing with prefix-encrypted blessings under the server's policy
- **Future work**: Mutual privacy in TLS 1.3

Unlinkability

request

Blessing: Alice/Family/Bob
Policy: **Allow** Alice/SecSys

Blessing: Alice/SecSys
Policy: **Allow** Alice/Family

Diffie-Hellman (DH) exchange

$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} \rangle\!\rangle_{\text{pol}} + \text{Signature}_{\text{SecSys}} \}_k$

$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Notation

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$\{m\}_k$:authenticated-encryption of m under key k.

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Unlinkability

request

Blessing: Alice/Family/Bob
Policy: **Allow** Alice/SecSys

Blessing: Alice/SecSys
Policy: **Allow** Alice/Family

Linkability Issues:
Signature reveals the server's public key to everyone

Prefix encryption reveals the server's policy to everyone

Diffie-Hellman (DH) exchange

$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} \rangle\!\rangle_{\text{pol}} + \text{Signature}_{\text{SecSys}} \}_k$

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$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Notation
k : key from DH secret

$\{m\}_k$:authenticated-encryption of m under key k.

$\langle\!\langle m \rangle\!\rangle_{\text{pol}}$: **anonymous** prefix encryption of m under pattern 'pol'.

Unlinkability

request

Blessing: Alice/Family/Bob
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Diffie-Hellman (DH) exchange

$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} + \text{Signature}_{\text{SecSys}} \rangle\!\rangle_{pol} \}_k$

$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Notation

k : key from DH secret

$\{m\}_k$:authenticated-encryption of m under key k.

$\langle\!\langle m \rangle\!\rangle_{pol}$: **anonymous** prefix encryption of m under pattern 'pol'.

This protocol offers both mutual privacy and unlinkability

Unlinkability

request

Blessing: Alice/Family/Bob
Policy: **Allow** Alice/SecSys

Blessing: Alice/SecSys
Policy: **Allow** Alice/Family

Server overhead: One IBE Encryption per handshake

Client overhead: One or more IBE Decryptions per handshake

Diffie-Hellman (DH) exchange

$\{ \langle\!\langle \text{Blessing}_{\text{SecSys}} + \text{Signature}_{\text{SecSys}} \rangle\!\rangle_{pol} \}_k$

$\{ \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}} \}_k$

Notation

k : key from DH secret

$\{m\}_k$:authenticated-encryption of m under key k.

$\langle\!\langle m \rangle\!\rangle_{pol}$: **anonymous** prefix encryption of m under pattern 'pol'.

Efficiency-Unlinkability trade-off

Private Service Discovery

Private and authentic service advertisements

Simple protocol

- Service signs its advertisement and IBEncrypts it under its policy

- Clients then connect to service using private mutual authentication
  - Why private mutual authentication?
  - Answer: To defend against port-scanning attacker

But this is too expensive,
Can we avoid a full blown private mutual authentication?

Idea

$$\langle\!\langle\ \text{ServiceData} + g^s + \text{Blessing}_{\text{SecSys}} + \text{Signature}_{\text{SecSys}}\ \rangle\!\rangle$$

$$\text{pol}$$

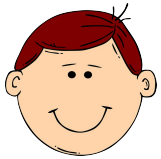
- Service includes a (semi-static) DH share (g^s) in the advertisement
- It signs the advertisement and encrypts it under its prefix policy

This allows clients to authenticate to the server and set up an encrypted channel to it in zero roundtrips (0-RTT)

Private Service Discovery

$\langle\!\langle$ ServiceData + g^s + $\text{Blessing}_{\text{SecSys}}$ + $\text{Signature}_{\text{SecSys}}$ $\rangle\!\rangle$

pol



bid + sid + g^x + $\{$ $\text{Blessing}_{\text{SecSys}}$ + $\text{Blessing}_{\text{Bob}}$ + $\text{Signature}_{\text{Bob}}$ $\}_{k1}$

$k1 := KDF(g^x, g^s, g^{xs}, 1)$

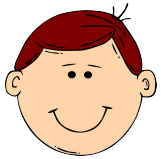
$k2 := KDF(g^x, g^s, g^{xs}, 2)$

$k3 := KDF(g^x, g^s, g^{xs}, 3)$

Private Service Discovery

$\langle\!\langle$ ServiceData + g^s + $\text{Blessing}_{\text{SecSys}}$ + $\text{Signature}_{\text{SecSys}}$ $\rangle\!\rangle$

~~pol~~



bid + sid + g^x + $\{\text{Blessing}_{\text{SecSys}} + \text{Blessing}_{\text{Bob}} + \text{Signature}_{\text{Bob}}\}_{k1}$

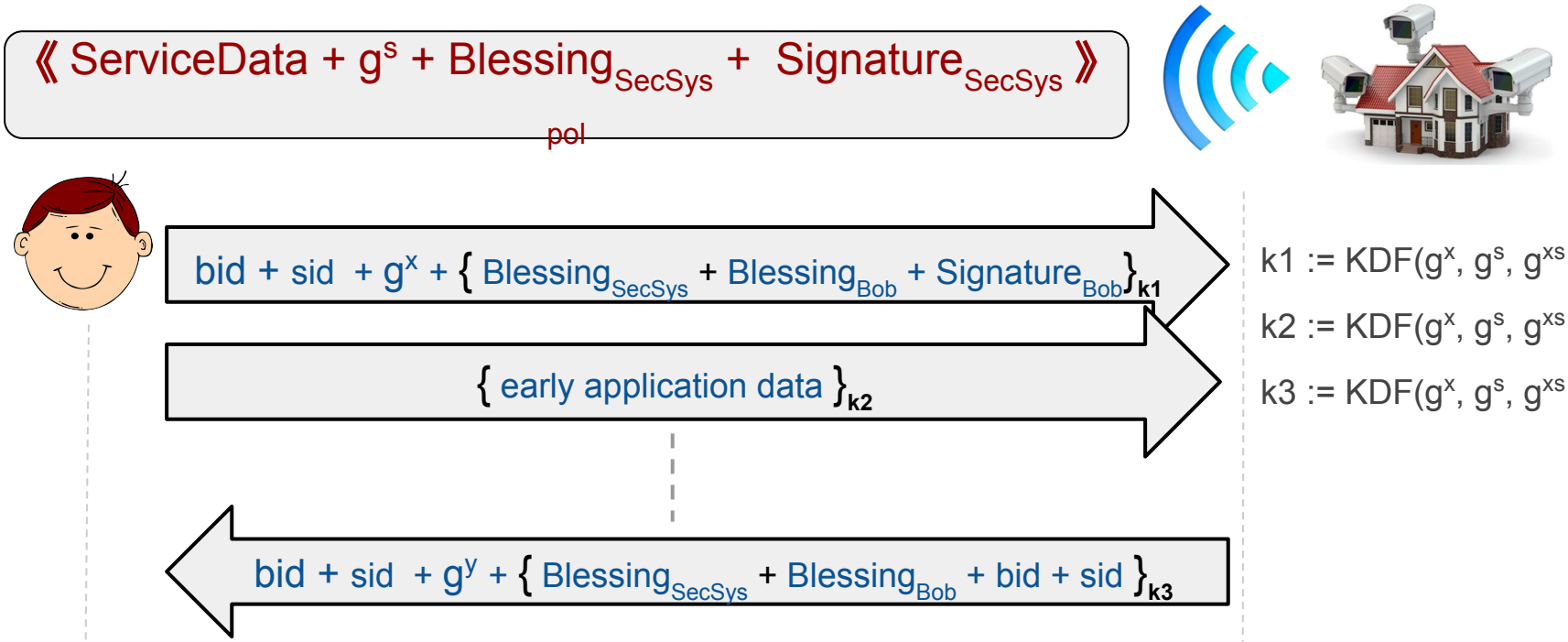
$\{$ early application data $\}_{k2}$

k1 := KDF(g^x, g^s, g^{xs} , 1)

k2 := KDF(g^x, g^s, g^{xs} , 2)

k3 := KDF(g^x, g^s, g^{xs} , 3)

Private Service Discovery



Analysis

Theorem: *Protocol satisfies key-exchange security and mutual identity privacy in the Canetti-Krawcyzk model*

- Private and authentic service advertisements
- 0-RTT mutual authentication

Limitations

- Perfect forward secrecy lost for early application data
- Replay attacks against server’s advertisements
  - Add an expiry time to the broadcast
  - Maintain a log of “used” client nonces at the server
  - This is a challenge for all 0-RTT protocols (e.g., TLS 1.3, QUIC)

Implementation and Benchmarks

Implementation

We implemented the following in the Vanadium framework

- Boneh-Boyen (BB1, BB2) IBE schemes over “bn256” pairings along with the Fujisaki-Okamoto transformation for CCA2 security
- Prefix-encryption on top of IBE
- Private mutual authentication protocol (without unlinkability) using prefix encryption
- Private discovery protocol using prefix encryption

IBE benchmarks

	Intel Edison	Raspberry Pi 2	Nexus 5X*	Laptop	Desktop
Pairing	254.5 ms	101.2 ms	219.2 ms	5.0 ms	1.0 ms
Encrypt	406.7 ms	157.2 ms	161.3 ms	8.2 ms	3.5 ms
Decrypt	623.0 ms	235.2 ms	235.7 ms	11.6 ms	3.7 ms
Extract	107.5 ms	41.6 ms	47.2 ms	2.1 ms	0.5 ms

⋆ Unoptimized Go implementation of `bn256`.

Intel Edison : 0.5GHz Intel Atom processor
RaspberryPi2 : 0.9GHz ARM Cortex-A7
Nexus5X : 3.1GHz Intel Core i7

Private mutual authentication benchmarks

- Run client and server on the same device
- Pre-compute encryption of server blessings under server's policy

	Intel Edison	Raspberry Pi 2	Nexus 5X	Laptop	Desktop
SIGMA-I	252.1 ms	88.0 ms	91.6 ms	6.3 ms	5.3 ms
Private Mutual Auth.	1694.3 ms	326.1 ms	360.4 ms	19.6 ms	9.5 ms
Slowdown	6.7x	3.7x	3.9x	3.1x	1.8x

Intel Edison : 0.5GHz Intel Atom processor
RaspberryPi2 : 0.9GHz ARM Cortex-A7
Nexus5X : 3.1GHz Intel Core i7

Private Service Discovery Benchmarks

$$\text{bid} + \langle\!\langle\, \text{ServiceData} + g^{s} + \text{Blessing}_{\text{SecSys}} + \text{Signature}_{\text{SecSys}} \,\rangle\!\rangle_{\text{pol}}$$

Advertisement processing time

1 IBE Decryption + 1 ECDSA verification

E.g., on a Nexus 5x: 236ms + 11ms = 247ms

Private Service Discovery Benchmarks

$$\text{bid} + \langle\!\langle\ \text{ServiceData} + g^{s} + \text{Blessing}_{\text{SecSys}} + \text{Signature}_{\text{SecSys}}\ \rangle\!\rangle_{pol}$$

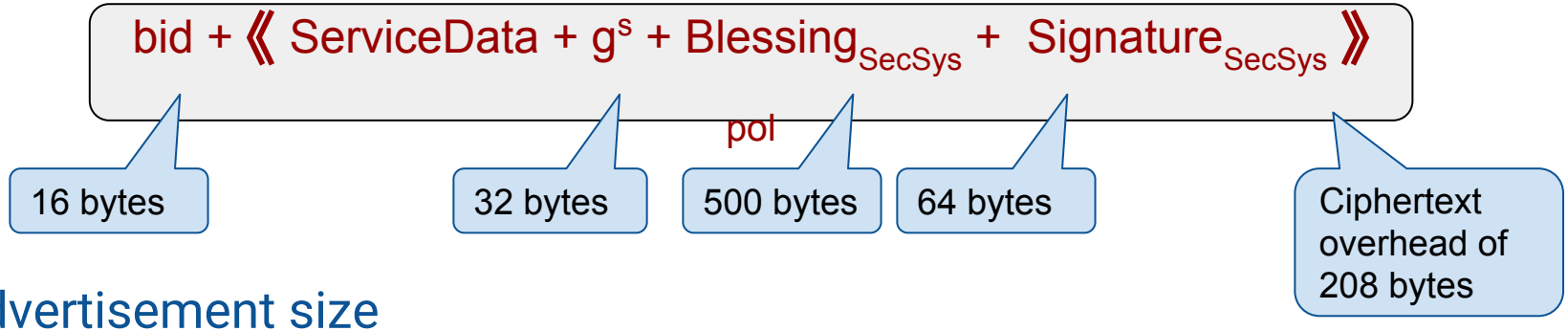
Advertisement size

- 820bytes for a single policy pattern
- 628 + 240*n when there are n patterns

But, mDNS packet limit is 1300 bytes and BLE is 30 bytes

- Start an auxiliary service to host the advertisement
- Advertise the endpoint of this auxiliary service over BLE or Wifi

Private Service Discovery Benchmarks



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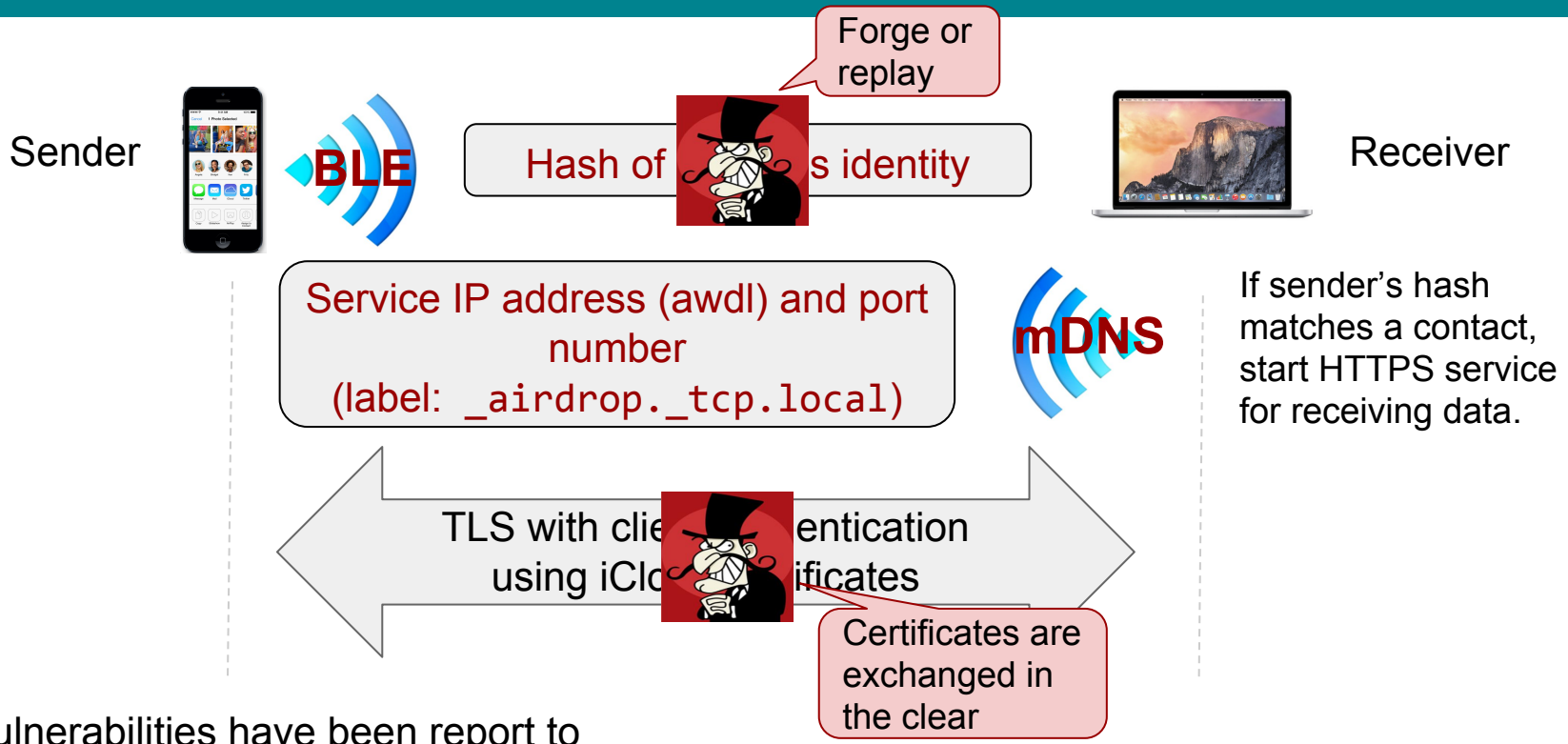
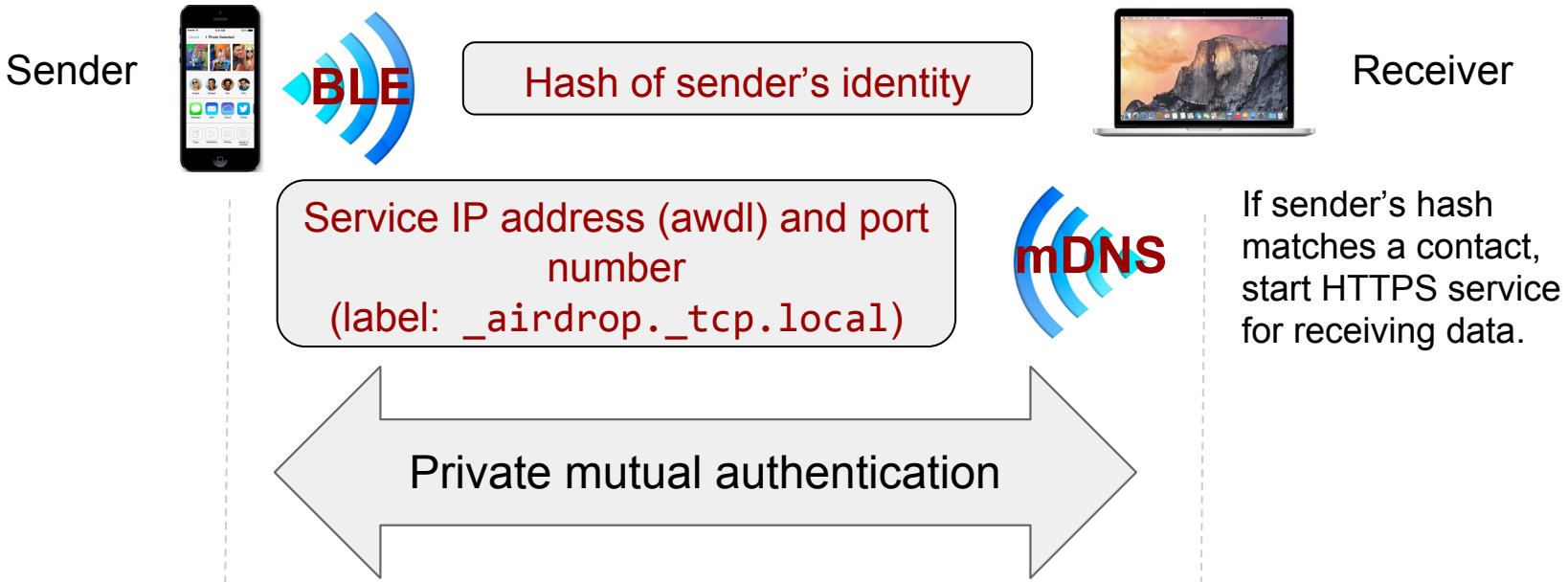
Fixing Apple AirDrop

AirDrop (contacts-only mode) vulnerabilities



Vulnerabilities have been report to Apple, awaiting response

Fixing AirDrop (contacts-only mode)



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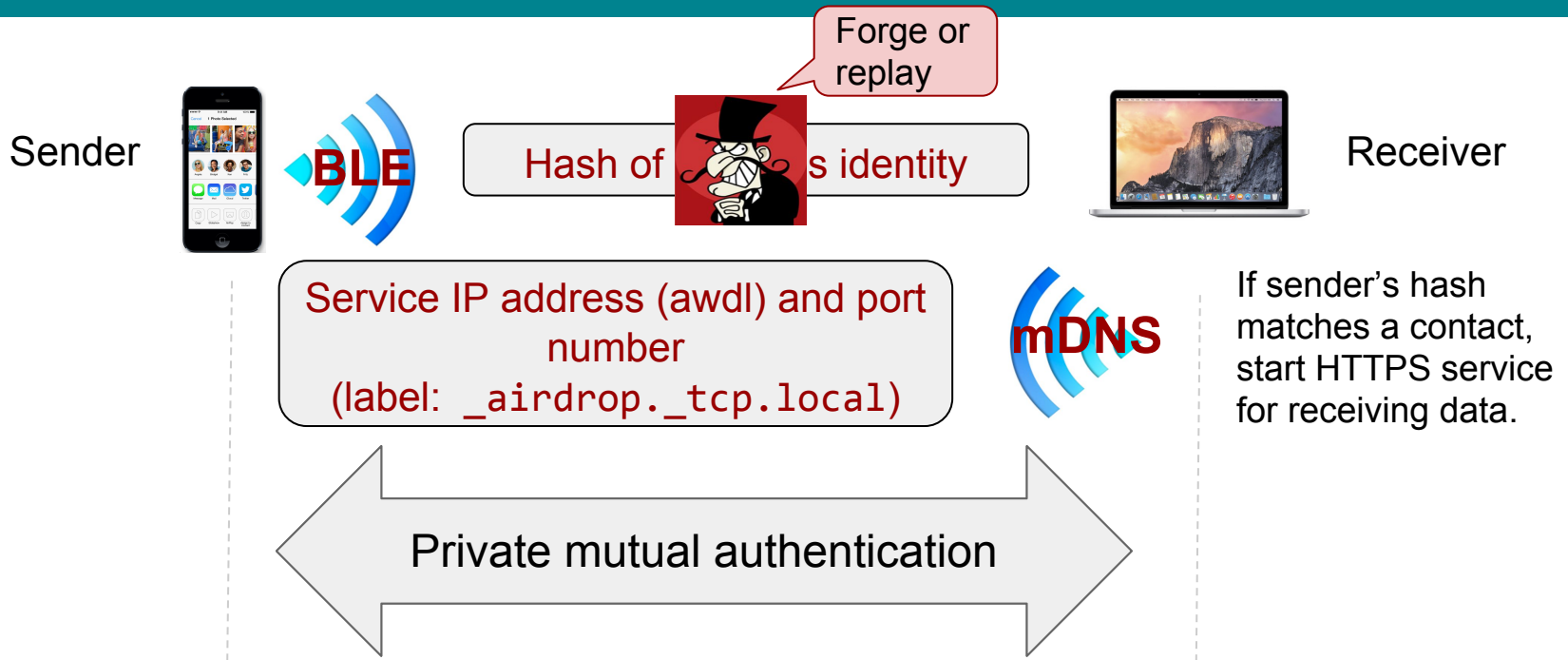


Fix reported to Apple, awaiting response

Practicalities

Revocation

How do we revoke Bob's prefix-encryption key?

Idea: Include a timestamp in the prefix pattern

- e.g., encrypt under Alice/Family/<2 Sept 2016>
- Bob will exchange his blessing for a new private key every day
- IBE root will stop issuing keys once Bob is revoked

Revocation

But even after revocation, old ciphertexts can be decrypted by Bob!

Idea: Include a unique nonce in the prefix pattern for each ciphertext

- e.g., encrypt under Alice/Family/<nonce>
- Bob will have to obtain a new private key for each ciphertext
- IBE root will stop issuing keys once Bob is revoked
- After revocation, Bob cannot decrypt ciphertexts he hasn't seen before

Revocation

What if the IBE master private key needs to be revoked ??

No easy solution :-(

- Rotate master private key and associated public params
- Inform all clients about the new params

Private key escrow

IBE Root can generate private keys for any identity and therefore decrypt all ciphertexts

Approaches

- Double encryption [Gentry, Eurocrypt 2003]
- Each user is an IBE Root
  - Need key servers to distribute params :-(
  - Can still use IBExtract locally to delegate keys

Perspective

- Privacy is a growing concern for the Internet of Things
- Privacy issues in authentication and discovery are still largely ignored
- IBE is far more practical than before, thanks to improved crypto algorithms and better hardware
- Still several trade-offs in the design, lots of opportunities for research

Privacy, Discovery, and Authentication for the Internet of Things,
David Wu, Ankur Taly, Asim Shankar, Dan Boneh [ESORICS 16]

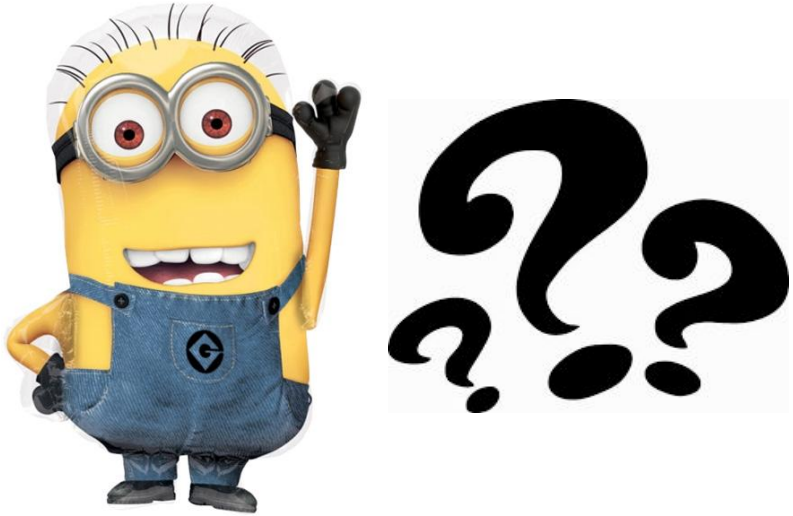
Further reading

Private Authentication --- Abadi and Fournet, 2004

Secret handshakes from pairing-based key agreements --- Balfanz et al., 2003

SIGMA: The “SIGn-and-MAc” approach to authenticated Diffie-Hellman and its use in the IKE-protocols --- Krawczyk, 2003

Questions



email: ataly@google.com

Thank You!