Anonymous & Unobservable Communication

https://dud.inf.tu-dresden.de/sac2

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(Slides [mainly] created by Andreas Pfitzmann)

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**Seminar: Privacy in Online Social Networks**

| Seminar: Privacy in Online Social Networks          | Strufe               |         |

| Seminar: Privacy and Security                       | Köpsell et.al.       | 2/0     |
| Seminar: Secure app. development                    | Borcea-Pfitzmann      | 2       |
| Seminar: Security in Computer Systems               | Köpsell              | 2       |
| Introduction to Data Protection Law                 | Wagner                | 2/0     |
Principles of PETs

- Privacy-enhancing Technologies (PETs)
  - Information suppression tools (Opacity tools)
  - Transparency-enhancing tools (TETs)

- Opacity Tools:
  - Anonymization, pseudonymization, obfuscation

- Transparency-enhancing Tools:
  - Informing user about data collection, purpose etc.
  - Informing about impact of data collection (needed for “informed consent“)
  - Enables checks whether data collection is conform to legal regulation
  - Various techniques: Secure Logging, Audits, Quality Seals, Policies etc.
Transparency-enhancing Tool
Protection Goals: Definitions

**Confidentiality** ensures that nobody apart from the communicants can discover the content of the communication.

**Hiding** ensures the confidentiality of the transfer of confidential user data. This means that nobody apart from the communicants can discover the existence of confidential communication.

**Anonymity** ensures that a user can use a resource or service without disclosing his/her identity. Not even the communicants can discover the identity of each other.

**Unobservability** ensures that a user can use a resource or service without others being able to observe that the resource or service is being used. Parties not involved in the communication can observe neither the sending nor the receiving of messages.

**Integrity** ensures that modifications of communicated content (including the sender’s name, if one is provided) are detected by the recipient(s).

**Accountability** ensures that sender and recipients of information cannot successfully deny having sent or received the information. This means that communication takes place in a provable way.

**Availability** ensures that communicated messages are available when the user wants to use them.

**Reachability** ensures that a peer entity (user, machine, etc.) either can or cannot be contacted depending on user interests.

**Legal enforceability** ensures that a user can be held liable to fulfill his/her legal responsibilities within a reasonable period of time.
• Anonymity:
  – is the state of being not identifiable within a set of subjects, the *anonymity set*.
  – is the stronger, the larger the respective anonymity set is and the more evenly distributed the sending or receiving, respectively, of the subjects within that set is.

⇒ *Anonymity* within a particular setting depends on the number of users
• **Unlinkability:**
  - of two or more items of interest (IOIs, e.g., subjects, messages, actions, ...) from an attacker’s perspective means that within the system, the attacker cannot sufficiently distinguish whether these IOIs are related or not.

⇒ **Anonymity in terms of Unlinkability:**
  Unlinkability between an identity (subject) and the IOI in question (message, data record etc.)
Correlations between protection goals

Confidentiality → Hiding

Confidentiality + Anonymity

Anonymity → Unobservability

Integrity → Availability

Accountability → Reachability

Legal Enforceability

implysthe

strengthens

weakens
Observability of users in switched networks

countermeasure encryption

- link encryption

- possible attackers
  - operator
  - manufacturer (Trojan horse)
  - employee
Observability of users in switched networks

countermeasure encryption
  • end-to-end encryption

radio

radio

network termination

interceptor

(telephone) exchange
  • operator
  • manufacturer (Trojan horse)
  • employee

possible attackers

television

videophone

phone

internet
countermeasure encryption

- link encryption
- end-to-end encryption

**Problem:** traffic data
who with whom?
when? how long?
how much information?

**Aim:** “protect” traffic data (and so data on interests, too) so that they couldn’t be captured.
Reality or fiction?

Since about 1990 reality

Video-8 tape 5 Gbyte
= 3 * all census data of 1987 in Germany
memory costs < 25 EUR

100 Video-8 tapes (or in 2018: 1 hard drive disk with 500 GByte for ≈ 22 EUR) store
all telephone calls of one year:

Who with whom ?
When ?
How long ?
From where ?
With the development of television, and the technical advance which made it possible to receive and transmit simultaneously on the same instrument, private life came to an end.

George Orwell, 1948
Examples of changes w.r.t. anonymity and privacy

Broadcast allows recipient anonymity — it is not detectable who is interested in which programme and information
Examples of changes w.r.t. anonymity and privacy

Internet-Radio, IPTV, Video on Demand etc. support profiling
Remark: Plain old letter post has shown its dangers, but nobody demands full traceability of them …
The massmedia „newspaper“ will be personalised by means of Web, elektronic paper and print on demand.
Privacy & the Cloud?

[http://www.apple.com/icloud/]
Smart Home
Smart Car
Smart Watch
Smart TV
Smart ...

http://www.digitaltrends.com/home/google-just-bought-nest-3-2-billion/

http://www.bmw.de/de/topics/faszination-bmw/connecteddrive/ubersicht.html
Types of Data

- Data without any *relation* to *individuals*
  - Simulation data
  - Measurements from experiments

- Data *with relation to individuals*
  - Types
    - Content
    - Meta data
  - Revelation
    - Consciously
    - Unconsciously
Notions of Privacy: Right to be let alone


- **Reason:** “snapshot photography” (recent innovation at that time)
  - allowed newspapers to publish photographs of individuals without obtaining their consent.
  - private individuals were being continually injured
  - this practice weakened the “moral standards of society as a whole”

- **Consideration:**
  - basic principle of common law: individual shall have full protection in person and in property
  - “it has been found necessary from time to time to define anew the exact nature and extent of such protection”
  - “Political, social, and economic changes entail the recognition of new rights”

- **Conclusion:**
  - “right to be let alone”
Notions of Privacy: Data Protection

- **Principles**
  - collect and process personal data *fairly and lawfully*
  - **purpose binding**
    - keep it only for one or more specified, explicit and lawful purposes
    - use and disclose it only in ways compatible with these purposes
  - **data minimization**
    - adequate, relevant and not excessive wrt. the purpose
    - retained no longer than necessary
  - **transparency**
    - inform who collects which data for which purposes
    - inform how the data is processed, stored, forwarded etc.
  - **user rights**
    - access to the data, correction, deletion
  - keep the data safe and secure
Notions of Privacy: Contextual Integrity

• Helen Nissenbaum: *Privacy as Contextual Integrity*, Washington Law Review, 2004

• close relation to data protection principles:
  – purpose binding

• Idea:
  – privacy violation, if:
    • violation of **Appropriateness**
      – the context „defines“ if revealing a given information is appropriate
      – **violation:** usage of information disclosed in one context in another context (even if first context is a “public” one)
    • violation of **Distribution**
      – the context „defines“ which information flows are appropriated
      – **violation:** inappropriate information flows
Degress of Anonymity


• exemplified with sender anonymity:
  – beyond suspicion: no more likely than any other potential sender
  – probable innocence: no more likely to be the sender than not to be the sender
  – possible innocence: there is a nontrivial probability that the real sender is someone else
Protection outside the network

Public terminals
  – use is cumbersome

Temporally decoupled processing
  – communications with real time properties

Local selection
  – transmission performance of the network
  – paying for services with fees

Protection inside the network
Questions:

• How widely distributed? (stations, lines)
• observing / modifying?
• How much computing capacity? (computationally unrestricted, computationally restricted)
Realistic protection goals/attacker models:
Technical solution possible?
Questions:

• How widely distributed? (stations, lines)
• observing / modifying?
• How much computing capacity? (computationally unrestricted, computationally restricted)

Unobservability of an event $E$

For attacker holds for all his observations $B$: $0 < P(E|B) < 1$

perfect: $P(E) = P(E|B)$

Anonymity of an entity

Unlinkability of events

if necessary: partitioning in classes
### Protection of the recipient: Broadcast

#### Performance?
- more capable transmission system

#### Addressing
- **explicit addresses:** routing
- **implicit addresses:** attribute for the station of the addressee

<table>
<thead>
<tr>
<th>Address Distribution</th>
<th>Public Address</th>
<th>Private Address</th>
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<tr>
<td><strong>Invisible</strong></td>
<td>very costly, but necessary to establish contact</td>
<td>costly</td>
</tr>
<tr>
<td><strong>Visible</strong></td>
<td>should not be used</td>
<td>change after use</td>
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- **invisible** <-> encryption system
  - example: pseudo random number (generator), associative memory to detect

- **private address**
- **public address**

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A. Pfitzmann, M. Waidner 1985
BitMessage (J. Warren, 2012)

- messaging system based on
  - broadcast
  - implicit invisible private addresses
- python based clients at: bitmessage.org
- address: \texttt{Hash(public encryption key, public signature test key)}
- messages:
  - encrypted using Elliptic Curve Cryptography
  - digitally signed
  - additionally: proof of work
  \( \Rightarrow \) Anti-SPAM
- broadcast of messages:
  - P2P-based overlay structure
  - store-and-forward like
  - pull-based
Equivalence of Encryption Systems and Implicit Addressing

invisible public address \iff \text{asymmetric encryption system}

invisible private address \iff \text{symmetric encryption system}
Broadcast vs. Queries

Broadcast of separate messages to all recipients

Everybody can query all messages
Example for message service

5 servers available, all contain the same messages in equal order

3 servers used for superposed querying

servers add responses, which are encrypted with (pseudo-) one-time pads

response of the message service:

\[ !x = \text{message 1 XOR message 4} \]
\[ !y = \text{message 1 XOR message 2} \]
\[ !z = \text{message 2 XOR message 3 XOR message 4} \]

from this follows by local superposition of the pads

\[ !x \oplus !y \oplus !z \Rightarrow \text{message 3} \]

(equal to the sum of the wanted (**))

memory cells

message service

Pseudo Random Short

generated by servers themselves when starting circulation

bit position corresponds to memory cell

invert bit of the memory cell of interest

query vectors

query multiple memory cells

servers add responses, which are encrypted with (pseudo-) one-time pads

3 servers used for superposed querying

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\[ !x \oplus !y \oplus !z \Rightarrow \text{message 3} \]

(equal to the sum of the wanted (**))

memory cells
User is interested in D[2]:

Index within Request-Vector = 1234
Set Vector = 0100
Chose random Vector (S1) = 1011
Chose random Vector (S2) = 0110
Calculate Vector (S3) = 1001

Calculations: XOR

c_{S1}(1011)
c_{S2}(0110)
c_{S3}(1001)
User is interested in D[2]:

Index within Request-Vector = 1234

Set Vector = 0100
Chose random Vector (S1) = 1011
Chose random Vector (S2) = 0110
Calculate Vector (S3) = 1001

Server calculates XOR of the requested records

Answer of S1: 0010110
S2: 1001000
S3: 0111000

Sum is D[2]: 1100110

Note: Encryption between Server and Client necessary!
Example for message service

5 servers available, all contain the same messages in equal order

server, which gets the long query vector, starts circulation

servers add responses, which are encrypted with (pseudo-) one-time pads

3 servers used for superposed querying

response of the message service:

\[ !x = \text{message 1} \oplus \text{message 4} \]
\[ !y = \text{message 1} \oplus \text{message 2} \]
\[ !z = \text{message 2} \oplus \text{message 3} \oplus \text{message 4} \]

from this follows by local superposition of the pads

\[ !x \oplus !y \oplus !z = \text{message 3} \]

(equal to the sum of the wanted (**) memory cells)

David A. Cooper, Kenneth P. Birman 1995
Efficiency improvements: A. Pfitzmann 2001
"Query and superpose" instead of "broadcast"

re-writable memory cell = implicit address
re-writing = addition mod 2 (enables to read many cells in one step)
channels trivially realizable

Purposes of implicit addresses

Broadcast: Efficiency (evaluation of implicit address should be faster than processing the whole message)
Query and superpose: Medium Access Control; Efficiency (should reduce number of messages to be read)

fixed memory cell = visible implicit address

implementation: fixed query vectors for servers 0 \rightarrow 1

Number of addresses \textit{linear} in the expense (of superposing).

Improvement: Set of re-writable memory cells = implicit address

Message \( m \) is stored in a set of \( a \) memory cells by choosing \( a-1 \) values randomly and choosing the value of the \( a^{\text{th}} \) cell such that the sum of all \( a \) cells is \( m \).

For overall \( n \) memory cells, there are now \( 2^n-1 \) usable implicit addresses, but due to overlaps of them, they cannot be used independently. If collisions occur due to overlap, try retransmit after randomly chosen time intervals. Any set of cells as well as any set of sets of cells can be queried in one step.
Invisible implicit addresses using “query and superpose” (1)

hopping between memory cells = invisible implicit address

Idea: User who wants to use invisible implicit address at time \( t \)
reads the values from reserved memory cells at time \( t-1 \).
These values identify the memory cell to be used at time \( t \).

Impl.: • Address owner gives each server \( s \) a \( PBG_s \).
• Each server \( s \) replaces at each time step \( t \) the content of its
reserved memory cell \( S_{Adr} \) with \( PBG_s(t) \):

\[
S_{Adr} := PBG_s(t)
\]

• User queries via MIXes \( \sum_s PBG_s(t) \). (possible in one step.)
user employs \( \sum_s PBG_s(t) \) for message. ✓✓1

• Address owner generates \( \sum_s PBG_s(t) \) and reads using “query and superpose”

\[
\sum_s PBG_s(t)
\]

Improvement: for all his invisible implicit addresses together: ✓✓2 (if \( \leq 1 \) msg)

Address is in so far invisible, that at each point of time only a very little fraction of
all possible combinations of the cells \( S_{Adr} \) are readable.
Invisible implicit addresses using “query and superpose” (2)

hopping between memory cells = invisible implicit address

can be extended to

hopping between sets of memory cells = invisible implicit address
Fault tolerance (and countering modifying attacks)

What if server (intentionally) does

1. not respond or

2. delivers wrong response?

1. Submit the same query vector to another server.

2. Messages should be authenticated so the user can check their integrity and thereby detect whether at least one server did deliver a wrong response. If so, use a disjoint set of servers or lay traps by sending the same query vector to many servers and checking their responses by comparison.
Protection of the sender

Dummy messages

- don’t protect against addressee of meaningful messages
- make the protection of the recipient more inefficient

Unobservability of neighboring lines and stations as well as digital signal regeneration

example: RING-network
Proof of anonymity for a RING access method

Flow of the message frame around the ring

Digital signal regeneration:

The analogue characteristics of bits are independent of their true sender.

The idea of physical unobservability and digital signal regeneration can be adapted to other topologies, i.e. tree-shaped CATV networks;

It reappears in another context in Crowds, GNUnet, etc.

Digital signal regeneration:

The analogue characteristics of bits are independent of their true sender.
Crowds (Reiter, Rubin, 1998)

- Goal: Anonymous Web browsing
- Link-Encryption between two participants
- HTTP-requests /-responses in plain (no end-to-end encryption)
- each user makes random routing decision

Diagram:

1. HTTP-Request
2. HTTP-Request
3. HTTP-Request
4. HTTP-Request
5. HTTP-Response
6. HTTP-Response

User A → Blender → User B → Blender → User C ← Blender ← User E ← Blender ← User D

Blender

- A Registration of Jondo
- B Acknowledgment; List of registered Jondos

Web-Server I
Web-Server II
Web-Server III
User A

User B

User C

User D

User E

User F

User G

User H

1. Request \( h(h(h(B)))) \) for block B

2. Indirecting of a request (sender address will be rewritten)

3. Forwarding of a request (original sender address is preserved)

4. Link encrypted communication between two adjoining GNUnet users

5. Response to user according to the given sender address

6. Encrypted block \( B_{enc}=E_{h(B)}(B) \)
Buses...

- Amos Beimel, Shlomi Dolev: „Buses for Anonymous Message Delivery“, 2002
  - follow-up: Andreas Hirt, Michael J. Jacobson, Jr., Carey Williamson: “A practical buses protocol for anonymous internet communication.”, 2005

- basic ideas follow a city-bus metaphor
  - messages send around contain „seats“, i.e cells dedicated to certain users/messages
  - different protocols proposed: trade-of: communication complexity, time complexity, storage complexity
Buses...

- **Attacker model:**
  - global observing outsider
  - observing participants (except sender/receiver!)
  - [modifying attackers are only considered wrt. availability]

- **Protection goals achieved**
  - sender anonymity
  - recipient anonymity
  - unobservability regarding sending/receiving of messages
Buses
Buses – simple solution

- dummy messages, if nothing to sent
- implicit addressing
- communication complexity: 1
- time complexity: $O(n)$
- storage complexity: $O(n^2)$
1. Idea: just one „seat“ per sender
   - one ring per sender, i.e. broadcast using implicit addresses

2. Idea: sender selects random „seat“
   - problem: replacement of message from other sender
   - birthday paradox
   - $s$ – number of messages sent simultaneously
   - $k$ – some security parameter
   - for bus size $b = k \cdot s^2 \rightarrow P\text{(collision)} \approx 1/k$
   - advantage: sender anonymity against recipient
   - crypto: layered (aka mix-based)
Buses – reduced seats – Example

- A wants to send some message $m$ to D
- depicted is one seat of the bus

- replay attacks!

$A$ wants to send some message $m$ to $D$
- $k_E^{-1}$(random)
- $k_B(k_C(k_D(m)))$
- $k_C(k_D(m))$
- $k_D(m)$
- $k_D(m)$
- random

- depicted is one seat of the bus
(Universal) Re-encryption


• Re-encryption:
  – given: public key \( e \), \( c = \text{Enc}(e, m) \)
  – create: \( c' = \text{Enc}(e, m) \) with \( c' \neq c \)

• Universal Re-encryption:
  – Re-encryption without knowing \( e \)
    \( \rightarrow \) avoids linkability (same recipient…)

• Implementation:
  – Recall ElGamal:
    • \( e = g^x \)
    • \( \text{Enc}(m) = (g^y, m \cdot e^y) \)
    • Homomorphic property: \( \text{Enc}(m_1) \cdot \text{Enc}(m_2) = \text{Enc}(m_1 \cdot m_2) \)
  – Re-encryption:
    • \( \text{Enc}(m)^z = (g^y \cdot g^z, m \cdot e^y \cdot e^z) = (g^{y+z}, m \cdot e^{y+z}) = (g^{y'}, m \cdot e^{y'}) \)
  – Universal Re-encryption:
    • Idea: \( \text{Enc}(m) = [ \text{Enc}(m), \text{Enc}(1) ] = [ (g^y, m \cdot e^y), (g^{y'}, e^{y'}) ] \)
    • \( \text{Enc}(m)^z \cdot z' = [ \text{Enc}(m) \cdot \text{Enc}(1)^z , \text{Enc}(1)^z' ] = [ (g^{y+y' \cdot z}, m \cdot e^{y+y' \cdot z}), (g^{y' \cdot z'}, e^{y' \cdot z'}) ] \)
      = [ (g^{y''}, m \cdot e^{y''}), (g^{y'''}, e^{y'''}) ] \)
(Threshold) Proxy Re-encryption

• Proxy Re-encryption:
  – given: \( c = \text{Enc}(e, m), e' \)
  – create: \( c' = \text{Enc}(e', m) \)
  ➔ Will not reveal plaintext \( m \)

• Threshold Proxy Re-encryption:
  – Proxy is distributed among \( n \) entities
  – \( k \) of \( n \) are necessary for re-encryption
  – Use case: plaintext \( m \) can only be read by the holder of \( e' \), iff at least \( k \) entities “agree”
Buses – reduced time complexity

- 2 buses per link
- messages a transferred from one bus to another according to the shortest path
- number of seats depends on the shortest paths from all senders to all receivers

4 seats → one per recipient of D

4 seats → one per sender of D

? seats → e.g. shortest path B to E not unique

- tradeoff: time vs. communication complexity
  ➔ spanning subgraph sufficient
Buses – time and communication tradoff

- Idea: partition graph into clusters, have one bus per cluster
• achieves sender and recipient anonymity

• basic building blocks:
  – random walk through peer graph
    • simulates broadcast
  – invisible implicit addressing
  – dummy messages
  – strict synchronisation
    • mitigates timing attacks
• dummy or real message

- store for decryption
- forward to random peer (--TTL)

• delete if TTL=0
Fault tolerance of the RING-network

Requirement
For each possible error, anonymity has to be guaranteed.

Problem
Anonymity: little global information
Fault tolerance: much global information

Principles
Fault tolerance through weaker anonymity in a single operational mode (anonymity-mode)
Fault tolerance through a special operational mode (fault tolerance-mode)
Braided RING

Two RINGs operating if no faults

Reconfiguration of the outer RING if a station fails

Reconfiguration of the inner RING if an outer line fails

Reconfiguration of the outer RING if an outer and inner line fails

Line used

Line not used

Line used to transmit half of the messages
Modifying attacks

- **modifying attacks at**
  - **sender anonymity**
    - extend the access method
  - **recipient anonymity**
  - **service delivery**
    - publish input and output
    - if dispute: reconfiguration

covered in RING-network by attacker model
Superposed sending (DC-network)

Anonymity of the sender

If stations are connected by keys the value of which is completely unknown to the attacker, tapping all lines does not give him any information about the sender.
If the coin is heads, then I paid.

If the coin is tails, then I paid.

Now I know one of them paid—but since I can’t see which side the coin landed on, I don’t know which one of them paid.
Dining Cryptographers

DC-Net – Superposed Sending

Chaum, 1988

Key Graph

A → C

B

True Message from A: 00110101
Key with B: 00101011
Key with C: 00110110
Sum: 00101000

A sends: 00101000

Empty Message from B: 00000000
Key with A: 00101011
Key with C: 01101111
Sum: 01000100

B sends: 01000100

Empty Message from C: 00000000
Key with A: 00110110
Key with B: 01101111
Sum: 01011001

C sends: 01011001

Sum = True Message from A: 00110101

Note: In this example, "sum" means XOR
Superposed sending (DC-network)

Anonymity of the sender

If stations are connected by keys the value of which is completely unknown to the attacker, tapping all lines does not give him any information about the sender.

D. Chaum 1985 for finite fields
A. Pfitzmann 1990 for abelian groups
Three distinct topologies

key topology independent of the others

superposition topology dependent on each other
Reservation scheme

<table>
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<tr>
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<th>S_1</th>
<th>S_2</th>
<th>S_3</th>
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<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

|   | 0   | 1   | 1   | 0   |

reservation frame

only different to “1” if “+” ≠ “⊕”

≥ one round-trip delay

time

message frame

T_5

T_4
Superposed receiving

Whoever knows the sum of \( n \) characters and \( n-1 \) of these \( n \) characters, can calculate the \( n \)-th character.

**pairwise superposed receiving** (reservation scheme: \( n=2 \))

Two stations send simultaneously.
Each subtracts their characters from the sum to receive the character sent by the other station.

\[ \Rightarrow \text{Duplex channel in the bandwidth of a simplex channel} \]

**global superposed receiving** (direct transmission: \( n \geq 2 \))

Result of a collision is stored, so that if \( n \) messages collide, only \( n-1 \) have to be sent again.

Collision resolution algorithm using the mean of messages:

\[ \leq 2^S - 1 \text{ station} \quad \text{addition mod } 2^L \]

<table>
<thead>
<tr>
<th>( S )</th>
<th>( S-1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ... 0</td>
<td>0 ... 0 1</td>
</tr>
</tbody>
</table>

overflow area for addition of messages

\( L \)

overflow area for addition of counters
Pairwise superposed receiving

\[ S_1 \]

\[ S_2 \]

\[ (X+Y)-X = Y \]

\[ (X+Y)-Y = X \]

without superposed receiving

with pairwise superposed receiving
Collision resolution algorithm with mean calculation and superposed receiving
Collision resolution algorithm with mean calculation and superposed receiving

Global superposed receiving (2 messages equal)

≥ one round-trip delay
Analogy between Vernam cipher and superposed sending

\[ K + M = C \iff M = C - K \]

abelian group

\[ M_1 + K = O_1 \]

\[ M_2 - K = O_2 \]
Proposition:

If stations $S_i$ are connected by uniform randomly distributed keys $K_j$ which are unknown to the attacker, by observing all the $O_i$, the attacker only finds out $\sum_i M_i$ about the $M_i$.

Proof:

$m=1$, trivial

step $m-1 \rightarrow m$
Proof of sender anonymity: induction step

Attacker observes $O_1, O_2, \ldots, O_m$.

For each combination of messages $M'_1, M'_2, \ldots, M'_m$
with $\sum_{i=1}^{m} M'_i = \sum_{i=1}^{m} O_i$ there is exactly one compatible combination of keys:

- $K' := O_m - M'_m$

- The other keys are defined as in the induction assumption, where the output of $S_L$ is taken as $O_L + K'$. 
Proof of sender anonymity: induction step

Attacker observes $O_1, O_2, ... O_m$.

For each combination of messages $M'_1, M'_2, ... M'_m$

with $\sum_{i=1}^{m} M'_i = \sum_{i=1}^{m} O_i$ there is exactly one compatible combination of keys:

- $K' := O_m - M'_m$

- The other keys are defined as in the induction assumption, where the output of $S_L$ is taken as $O_L + K'$. 
Information-theoretic anonymity in spite of modifying attacks

Problems:

1) The attacker sends messages only to some users. If he gets an answer, the addressee was among these users.

2) To be able to punish a modifying attack at service delivery, corrupted messages have to be investigated. But this may not apply to meaningful messages of users truthful to the protocol.
DC\(^+-\)net to protect the recipient even against modifying attacks: if broadcast error then uniformly distributed modification of keys

key between station \(i\) and \(j\) at time \(t\)

\[ K_{ij}^t = a_{ij}^t + \sum_{k=t-s}^{t-1} b_{ij}^{t-k} \cdot C_i^k \]

at station \(i\) at time \(t\)

broadcast character

For practical reasons:
Each station has to send within each \(s\) successive points in time a random message and observe, whether the broadcast is “correct“.
Modifying attacks

Modifying attacks at
sender anonymity
recipient anonymity
service delivery

attacker sends message character \( \neq 0 \),
if the others send their message character as well
\( \Rightarrow \) no transmission of meaningful information

To be able to punish a modifying attack at service delivery, corrupted messages have to be investigated. But this may \emph{not} apply to meaningful messages of users truthful to the protocol.
Each user can cause investigating the reservation blobs directly after their sending if the sending of his reservation blobs did not work.

Each user can authorize investigating of his “collision-free” random message, by opening the corresponding reservation blob.
Blob := committing to 0 or 1, without revealing the value committed to

1) The user committing the value must not be able to change it, but he must be able to reveal it.

2) The others should not get any information about the value.

In a “digital” world you can get exactly one property without assumptions, the other then requires a complexity-theoretic assumption.

Example:

Given a prime number $p$ and the prime factors of $p - 1$, as well as a generator $\alpha$ of $\mathbb{Z}_p^*$ (multiplicative group mod $p$). Using $y$ everybody can calculate $\alpha^y \mod p$.

The inverse can not be done efficiently!

1? 
$s \in \mathbb{Z}_p^*$ randomly chosen 
(so user cannot compute $e$ such that $s \equiv \alpha^e$)

$x := s^b \alpha^y \mod p$ with $0 \leq y \leq p - 2$
commit $x$
open $y$

2? 
Let $2^u$ be the smallest number that does not divide $p - 1$

$y := y_1, b, y_2$ with $0 \leq y \leq p - 2$ and $|y_2| = u - 1$

$x := \alpha^y \mod p$
commit $x$
open $y$
Blobs based on factoring assumption

1?
prover

verifier

\[ n := p \cdot q \]
\[ s := t^2 \mod n \]

\[ n, s \]
\[ s \in \text{QR}_n \]

commit

\[ x := y^2 s^b \mod n \]

open

\[ y \]

2?
prover

verifier

\[ n := p \cdot q \]
\[ s \notin \text{QR}_n, \left(\frac{s}{n}\right) = 1 \]

\[ n, s \]

\[ n=p\cdot q, s \notin \text{QR}_n \]

commit

\[ x := y^2 s^b \mod n \]

open

\[ y \]
Blobs based on asymmetric encryption system

2?
encrypt \( b \) with asymmetric encryption system (recall: public encryption key and ciphertext together uniquely determine the plaintext)

- has to be probabilistic – otherwise trying all possible values is easy
- communicating the random number used to probabilistically encrypt \( b \) means opening the blob
- computationally unrestricted attackers can calculate \( b \) (since they can break any asymmetric encryption system anyway)
Checking the behavior of the stations

To check a station it has to be known:

- All keys with others
- The output of the station
- All the global superposing results received by the station
- At what time the station may send message characters according to the access protocol
  (Can be determined using the global superposition results of the last rounds; These results can be calculated using the outputs of all stations.)

\[
\begin{align*}
\text{calculated message characters} & \quad \rightarrow \quad \text{compare} \\
\end{align*}
\]

known = known to \textit{all} stations truthful to the protocol
Collisions in the reservation phase
- cannot be avoided completely
- therefore they *must not* be treated as attack

Problem: Attacker A could await the output of the users truthful to the protocol and than A could choose his own message so that a collision is generated.

Solution: Each station
1. defines its output using a Blob at first, then
2. awaits the Blobs of all other stations, and finally
3. reveals its own Blob’s content.
Fault tolerance: 2 modes of operation

**A-mode**
- Anonymous transmission of messages using superposed sending

**F-mode**
- Sender and recipient are not protected

Fault detection

Error recovery of the PRGs, initialization of the access protocol

Fault localization

Taking defective components out of operation
Fault tolerance: sender-partitioned DC-network

Write and read access to the DC-network

Read access to the DC-network

Widest possible spread of a fault of station 3

... of a fault of station 5
Protection of the communication relation: MIX-network

D. Chaum 1981 for electronic mail

c1 (z4, M1)) -> c1 (z5, M2)) -> c1 (z6, M3))

MIX1 batches, discards repeats,
d1(c1(z,M)) = (z,M)

MIX2 batches, discards repeats,
d2(c2(z,M)) = (z,M)
Idea: Provide unlinkability between incoming and outgoing messages

A Mix collects messages, changes their coding and forwards them in a different order.

If all Mixes work together, they can reveal the way of a given messages.
Protection of the communication relation: MIX-network

MIX₁ batches, discards repeats,
\[ d₁(c₁(zᵢ, Mᵢ)) = (zᵢ, Mᵢ) \]

MIX₂ batches, discards repeats,
\[ d₂(c₂(zᵢ, Mᵢ)) = (zᵢ, Mᵢ) \]

D. Chaum 1981 for electronic mail
Basic functions of a MIX

- discard repeats
- buffer current input batch
- sufficiently many messages from sufficiently many senders? If needed: insert dummy messages
- re-encrypt (decrypt or encrypt)
- change order

MIX takes all input messages which were or will be re-encrypted using the same key.
Properties of MIXes

MIXes should be designed independently
produced
operated
maintained ...

Messages of the same length
buffer
re-encrypt
change order \(\text{batch-wise}\)

Each message processed only once!
inside each batch
between the batches

sym. encryption system only for
first \(\text{MIX}\)
last

asym. encryption system required
for MIXes in the middle
Aim: (without dummy traffic)

Communication relation can be revealed only by:

• all other senders and recipients together or
• all MIXes together which were passed through against the will of the sender or the recipient.

Conclusions:

1. Re-encryption: never decryption directly after encryption
   Reason: to decrypt the encryption the corresponding key is needed;
   ➔ before and after the encoding of the message it is the same
   ➔ re-encryption is irrelevant

2. Maximal protection:
   MIXes are passed through simultaneously and therefore in the same order
Mix-network topologies

- cascades: fixed chain of Mixes

- free routes of Mixes: random selection by sender
Mix-network topologies

- restricted routes:
  - dedicated set of last Mix (Tor: Exit-Node)
  - fixed first Mix (Tor: Entry-Guard)
  - restricted set of Node neighbours
Possibilities and limits of re-encryption

**Aim:** (without dummy traffic)

Communication relation can be revealed only by:

- *all* other senders and recipients together or
- *all* MIXes together which were passed through against the will of the sender or the recipient.

**Conclusions:**

1. **Re-encryption:** never decryption directly after encryption
   
   Reason: to decrypt the encryption the corresponding key is needed;
   
   ➔ before and after the encoding of the message it is the same
   
   ➔ re-encryption is irrelevant

2. **Maximal protection:**
   
   MIXes are passed through simultaneously and therefore in the same order
Maximal protection

Pass through MIXes in the same order
Maximal protection

Best case:

- Anonymity set size: 6
- 1 honest Mix
Maximal protection

Best case:
- Anonymity set size: 6
- 1 honest Mix

Alternative Architecture, therefore:
Pass through all honest MIXes in the same order.
Maximal protection

Best case:
- Anonymity set size: 6
- 1 honest Mix

Alternative Architecture, therefore:
Pass through all honest MIXes in the same order.
Problem: You don’t know which is honest…
Therefore:
Pass through all MIXes in the same order.
3 honest Mixes / Anonymity Set Size: 4
3 honest Mixes / Anonymity Set Size: 2
Re-encryption scheme for sender anonymity

\[ M_{n+1} = c_{n+1}(M) \]

\[ M_i = c_i(z_i, A_{i+1}, M_{i+1}) \quad \text{for} \quad i = n, \ldots, 1 \]

\[ M_i = c_i(k_i, A_{i+1}); k_i(M_{i+1}) \]
Indirect re-encryption scheme for recipient anonymity

\[ H_{m+1} = e \]
\[ H_j = c_j (k_j, A_{j+1}, H_{j+1}) \text{ for } j = m,..,0 \]

Message header \( H \)

Message content \( l \)

Encryption

Decryption

Observable transfer

Unobservable transfer
Indirect re-encryption scheme for sender and recipient anonymity

S -> MIX₁ -> MIX₂ -> MIX₃

MIX₄ -> MIX₅ -> R

message header

message content

for sender anonymity

for recipient anonymity

encryption

unobservable transfer

observable transfer

3rd party, to hold the anonymous return addresses for anonymous query
delivery using sender anonymity scheme

initiated using sender anonymity scheme

pickup using recipient anonymity scheme

3rd party, to hold the anonymous return addresses for anonymous query

k₁ k₂ k₃ k₄ k₅

k₁ k₂ k₃ k₄ k₅

k₁ k₂ k₃ k₄ k₅

k₁ k₂ k₃ k₄ k₅

k₁ k₂ k₃ k₄ k₅
Indirect re-encryption scheme maintaining message length

\[ H_{m+1} = [e] \]

\[ H_j = [c_j(k_j, A_{j+1}), k_j(H_{j+1})] \quad \text{for } j = m,..,1 \]
Indirect re-encryption scheme maintaining message length for special symmetric encryption systems

\[ M_j \]

\[ \begin{array}{cccc}
1 & 2 & 3 & \cdots \ m+2-j \\
\end{array} \]

\[ H_j \]

blocks with message contents

\[ k_j (H_{j+1}) \]

blocks with random contents

\[ Z_{j-1} \]

\[ M_{j+1} \]

\[ \begin{array}{cccc}
1 & 2 & \cdots \ m+1-j \\
\end{array} \]

\[ k_{j+1} (H_{j+2}) \]

blocks with message contents

\[ b-j \]

\[ b+1-j \]

\[ \cdots \]

\[ b \]

\[ Z_j \]

decrypt with \( d_j \)

re-encrypt with \( k_j \)

If \( k^{-1}(k(M)) = M \)

And \( k(k^{-1}(M)) = M \)
Minimally message expanding re-encryption scheme maintaining message length

$M_j\xrightarrow{k_j, A_{j+1}, C_j} M_{j+1}\xrightarrow{d_j}$

If $k^{-1}(k(M)) = M$ and $k(k^{-1}(M)) = M$
Mix Packets based on Diffie-Hellman Key Agreement

Recall: Diffie-Hellman key agreement

random number 1

key generation:
\( x \in \mathbb{Z}_p^* \)
\( g^x \mod p \)

calculating shared key
\( (g^y)^x \mod p \)

random number 2

key generation:
\( y \in \mathbb{Z}_p^* \)
\( g^y \mod p \)

calculating shared key
\( (g^x)^y \mod p \)

\( p, g \) publicly known:
\( p \) and \( g \in \mathbb{Z}_p^* \)

\( x \) \( g^x \mod p \)
\( y \) \( g^y \mod p \)

calculated keys are equal, because
\( (g^y)^x = g^{yx} = g^{xy} = (g^x)^y \mod p \)

Domain of trust

Area of attack
Recall: Diffie-Hellman key agreement – “modes of operation”

• static – static
  – sender & recipient use long time static DH keys

• ephemeral – static
  – recipient: long time static DH key
  – sender: newly create random DH-key („session key“)
  ➔ new DH secret with every key exchange
  ➔ ElGamal encryption system

• static – ephemeral

• ephemeral – ephemeral
  – sender & recipient use newly create random DH-keys
  ➔ forward secrecy
Mix Packets based on Diffie-Hellman Key Agreement

• first idea:
  – ephemeral – static mode
  – user creates DH key for every mix $M_i$:
    • $x_i, \ y_i \equiv g^{x_i} \mod p$
    • secret $k_i$ shared with $M_i$: $k_i \equiv y_M^{x_i} \mod p$
  – layered encryption:
    • $y_i, k_i(y_{i+1}, k_{i+1}(\ldots))$
  – overhead:
    • per mix: size of $y_i$
Mix Packets based on Diffie-Hellman Key Agreement

• more efficient idea:
  – ephemeral-static – static mode
    ➔ ephemeral: sender creates new DH key for every packet
    ➔ static: same DH key for all mixes!
  – user creates DH key (same for every mix $M_i$):
    • $x, y = g^x \mod p$
    • secret $k_i$ shared with $M_i$: $k_i = y_{M_i}^x \mod p$

  – layered encryption:
    • $y, k_i(k_{i+1}(...))$
Mix Packets based on Diffie-Hellman Key Agreement

• layered encryption:
  • $y, k_i(k_{i+1}(\ldots))$

• How to achieve?
  – Problem:
    • all mixes know $y$
      $\Rightarrow$ linkability!
  – Solution:
    • calculate $y_{i+1}$ from $y_i$
Mix Packets based on Diffie-Hellman Key Agreement

Solution:

- calculate $y_{i+1}$ from $y_i$
- $x_{i+1} = x_i b_i \mod p$
- $b_{i+1} = \text{Hash}(y_i, k_i)$


- $y_{i+1} = g^{x_{i+1}} \mod p$
  - $= g^{x_i b_i} \mod p$
  - $= y_i^{b_i} \mod p$

$\Rightarrow$ mix $M_i$ can calculate $y_{i+1}$ from $y_i$!

$\Rightarrow$ only $M_i$ can calculate $y_{i+1}$ from $y_i$!
Breaking the direct RSA-implementation of MIXes (1)

Implementation of MIXes using RSA without redundancy predicate and with contiguous bit strings (David Chaum, 1981) is insecure:

\[(z, M)^c \cdot f^c \equiv (z \cdot 2^B + M) \cdot f \equiv z \cdot 2^B \cdot f + M \cdot f.\]

Unlinkability, if many factors \(f\) are possible.

\[2^b \cdot 2^B \leq n-1\] hold always and normally \(b \ll B\).

If the random bit strings are the most significant bits, it holds

\[\begin{align*}
(z, M) &= z \cdot 2^B + M \\
(z, M) \cdot f &= (z \cdot 2^B + M) \cdot f \equiv z \cdot 2^B \cdot f + M \cdot f.
\end{align*}\]
Breaking the direct RSA-implementation of MIXes (2)

Let the identifiers $z'$ and $M'$ be defined by

$$(z,M)\cdot f \equiv z'\cdot 2^B + M' \Rightarrow$$

$$z\cdot 2^B \cdot f + M\cdot f \equiv z'\cdot 2^B + M' \Rightarrow$$

$$2^B \cdot (z\cdot f - z') \equiv M' - M\cdot f \Rightarrow$$

$$z\cdot f - z' \equiv (M' - M\cdot f) \cdot (2^B)^{-1} \quad (1)$$

If the attacker chooses $f \leq 2^b$, it holds

$$-2^b < z\cdot f - z' < 2^{2b} \quad (2)$$

The attacker replaces in (1) $M$ and $M'$ by all output-message pairs of the batch and tests (2).

(2) holds, if $b<<B$, very probably only for one pair (P1,P2). P1 is output message to $(z,M)^c$, P2 to $(z,M)^c\cdot f^c$.

If (2) holds for several pairs, the attack is repeated with another factor.
Fault tolerance in MIX-networks (1)

2 alternative routes via disjoint MIXes

MIX_{i} or MIX_{i}'' can substitute MIX_{i}

coordination protocol
Fault tolerance in MIX-networks (2)

In each step, one MIX can be skipped
### Complexity of the basic methods

<table>
<thead>
<tr>
<th>attacker model</th>
<th>RING-network</th>
<th>DC-network</th>
<th>MIX-network</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unobservability of neighboring lines and stations as well as digital signal regeneration</td>
<td><strong>computationally restricted w.r.t. service delivery</strong></td>
<td>computationally restricted not even well analyzed asymmetric encryption systems are known which are secure against adaptive active attacks</td>
</tr>
<tr>
<td>phys. limited</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>computationally restricted</strong></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td><strong>cryptographically strong</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>well analyzed</strong></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>expense per user</th>
<th>O(n) ( ≥ (\frac{n}{2})) transmission</th>
<th>O(n) ( ≥ (\frac{n}{2})) transmission</th>
<th>O(k), practically: (\approx 1) transmission on the last mile ... in the core network O(k^2), practically: (\approx k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(n)</td>
<td>O(n)</td>
<td>O(k \cdot n)</td>
<td>O(k), practically: (\approx 1) transmission on the last mile ... in the core network O(k^2), practically: (\approx k)</td>
</tr>
</tbody>
</table>

\(n = \) number of users

\(k = \) connectedness key graph of DC-networks respectively number of MIXes
In the OSI model it holds:

Layer \( n \) doesn’t have to look at Data Units (DUs) of layer \( n+1 \) to perform its service. So layer \( n+1 \) can deliver \((n+1)\)-DUs encrypted to layer \( n \).

For packet-oriented services, the layer \( n \) typically furnishes the \((n+1)\)-DUs with a \( n \)-header and possibly with an \( n \)-trailer, too, and delivers this as \( n \)-DU to layer \( n-1 \). This can also be done encrypted again.

and so on.

All encryptions are independent with respect to both the encryption systems and the keys.
Arranging it into the OSI layers (1)

OSI layers

| 0 medium |
| 1 physical |
| 2 data link |
| 3 network |
| 4 transport |
| 5 session |
| 6 presentation |
| 7 application |

Diagram:

- User station
- Exchange
- End-to-end encryption
- Link encryption
Arranging it into the OSI layers (2)

<table>
<thead>
<tr>
<th>OSI layers</th>
<th>broadcast</th>
<th>query</th>
<th>MIX-network</th>
<th>DC-network</th>
<th>RING-network</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 application</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 presentation</td>
<td></td>
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<tr>
<td>5 session</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4 transport</td>
<td>implicit addressing</td>
<td>implicit addressing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 network</td>
<td>broadcast</td>
<td>query and superpose</td>
<td>buffer and re-encrypt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 data link</td>
<td></td>
<td></td>
<td></td>
<td>anonymous access</td>
<td>anonymous access</td>
</tr>
<tr>
<td>1 physical</td>
<td>channel selection</td>
<td></td>
<td></td>
<td>superpose keys and messages</td>
<td></td>
</tr>
<tr>
<td>0 medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>digital signal regeneration</td>
</tr>
</tbody>
</table>

- **Yellow**: has to preserve anonymity against the communication partner
- **Green**: end-to-end encryption
- **Dark Orange**: has to preserve anonymity
- **Brown**: realizable without consideration of anonymity

has to preserve anonymity against the communication partner
end-to-end encryption
has to preserve anonymity
realizable without consideration of anonymity
Solution for the ISDN: telephone MIXes

**Aims: ISDN services on ISDN transmission system**
- 2 independent 64-kbit/s duplex channels on a 144-kbit/s subscriber line
- hardly any additional delay on established channels
- establish a channel within 3 s
- no additional traffic on the long distance network

**Network structure**

- 64+64+16=144 kbit/s duplex
- network termination
- local exchange LE(R)
- local exchange LE(G)
- legacy LE
Solution for the ISDN: telephone MIXes (1989)

**Aims: ISDN services on ISDN transmission system**
- 2 independent 64-kbit/s duplex channels on a 144-kbit/s subscriber line
- hardly any additional delay on established channels
- establish a channel within 3 s
- no additional traffic on the long distance network

**Network structure**

Network termination \( R \) \( \rightarrow \) local exchange \( LE(R) \)

\[ 64+64+16 = 144 \text{ kbit/s duplex} \]

long distance network

Network termination \( G \) \( \leftarrow \) local exchange \( LE(G) \)

\( \text{MIX}_1 \) \( \cdots \) \( \text{MIX}_m \) \( \text{MIX}'_{m'} \) \( \cdots \) \( \text{MIX}'_1 \)
Time-slice channels (1)

station R  MIXes(R)  LE(R)  station G

LE(G)  MIXes(G)

S₀

TS-setup: x
TR-setup: x

TS-setup: PBG(s₉,1)
TR-setup: PBG(s₉,1)

S₁

TS
TR

TS-setup: PBG(s₉,1)
TR-setup: PBG(s₉,1)

TS
TR

call request: c₉(k, s₉, and s₉)

query and superpose instead of broadcast

TR-setup: y

TS-setup: y
This setup of receiving channels is a very flexible scheme for recipient anonymity.
I2P — Invisible Internet Project

geti2p.net

NetworkDb (DHT)

<table>
<thead>
<tr>
<th>NetworkDb (DHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice 1 2</td>
</tr>
<tr>
<td>Bob 3 4</td>
</tr>
<tr>
<td>Dave 5 6</td>
</tr>
</tbody>
</table>

[https://geti2p.net/en/docs/how/intro]
Tor

- basic building block:
  - symmetric encrypted channels \(\rightarrow\) called: circuits
  - multiple streams multiplexed over one circuit

- Mix packet: cells
  - 512 bytes

- asymmetric crypto for key exchange: Diffie-Hellman
  - telescopically
    - CREATE-Cell sent to next Tor node over already established circuit
① establishes circuit
③ searches for introduction point
② publishes introduction point anonymously
④ establishes circuit
⑤ tells rendezvous point
⑥ establishes circuit
Connection configuration later (1)

station $R$ \hspace{1cm} MIXes($R$) \hspace{1cm} LE($R$) \hspace{1cm} LE($G$) \hspace{1cm} MIXes($G$) \hspace{1cm} station $G$

$S_0$

```
\begin{align*}
\text{TS-setup: } & x \\
\text{TR-setup: } & x \\
\end{align*}
```

call request: $c_G(k, s_R, \text{and } s_G)$

$S_1$

```
\begin{align*}
\text{TS-setup: } & \text{PBG}(s_G, 1) \\
\text{TR-setup: } & \text{PBG}(s_R, 1) \\
\end{align*}
```
Connection configuration later (2)

\[ S_2 \]
- **TS-setup**: PBG(sG,2)
- **TR-setup**: PBG(sR,2)
- **PBG(sR,1)**
- **throw away**
- **replace**

\[ S_{t-1} \]
- **TS-setup**: PBG(sG,t-1)
- **TR-setup**: PBG(sR,t-1)

\[ S_t \]
- **PBG(sR,t-1)**
- **PBG(sG,t-1)**
- **k(dial tone, data)**
Query and superpose to receive the call requests

Query and superpose:

- *Each* station has to query in each time slice (else the anonymity set degenerates).
- *Each* station should inquiry *all* its implicit addresses at each query.
  (possible both for visible and invisible addresses without additional expense)

→ The size of the anonymity set is no longer limited by the transmission capacity on the user line, but only by the addition performance of the message servers.
The AN.ON Project – est. in 2000

Goals:

- practical usable implementation of an anonymisation service
- protection against strong attackers

Foundation:

- Mix-technique invented by David Chaum (1981)

Cooperation:

- Technische Universität Dresden, Germany
- Independent Centre for Privacy Protection Schleswig-Holstein, Germany (ICPP) [privacy commissioner]
- JonDos GmbH, Germany (since 2007) [private company]
- Masaryk university, Brno, Czech republic (2009/2010)
Overview of the AN.ON system

- Distributed InfoService
- Bidirectional TCP/IP-connection

Users:
- User A
- User B
- User XYZ
User Interface of JAP

Services:
- Dresden (JAP)
- Alle Kaskaden (JonDonym)
- Premium-Kaskaden (JonDonym)
- Kostenfreie Kaskaden (JonDonym)
- Test/Experimental-Dienste

Benutzerdefinierter Filter:
- Dresden (JAP)

Remaining credit:

Encrypted data transferred: 119,8 kByte

Anti censorship service: Off
JAP Settings Dialog

### Anonymität

- **Mix-Standort:** Erfurt, Deutschland
- **Betreiber:** German Privacy Foundation e.V. (Deutschland)

**Filter anpassen**
- Anonymität: 2,6 / 6,6
- Nutzerrzahl: 999 / 1000
- Geschwindigkeit: 50 kbit/s
- Antwortzeit: ≤ 2000 ms
- Verfügbarkeit: Verbunden!
Mix-Protocol based on Chaumian Mixes & symmetric encrypted Channels

- MixChannel
  - reliable, connection oriented, full duplex
  - fragmented in many equal sized MixPackets

Protocol phases:

- **Connection establishment:**
  - initiated by the sender
  - tells each Mix a Channel-ID and a symmetric key

- **Data transmission:**
  - transmission of symmetric encrypted MixPackets

- **Connection close:**
  - initiated by sender or recipient

- for better performance all MixChannels are multiplexed over a single TCP/IP connection between JAP↔Mix and Mix↔Mix
Mix-Protocol

Addressing of the Communication Partner:
- only *Classes of Proxies* (e.g. a HTTP proxy)
  - proxies for “plain” TCP/IP available
- Advantage: Functionality of existing proxies could be reused
  - example WWW: Caching
  - in general: access control, Quality of Service etc.
  - many applications are able to speak a proxy protocol
    - but some are not...

Cryptography:
- each Mix has a long term (DSA-) signature key, which is used as “digital identity” of this Mix
- asymmetric encryption: 1024 bit RSA
- symmetric encryption: AES-128-OFB
Encryption in AN.ON

- **link layer encryption between Mix ↔ Mix and JAP ↔ Mix**
  - only header of each MixPacket
    - Reason: payload is already (multiple times) encrypted
  - Algorithm: AES-128-OFB
    - key exchange was done during cascade setup / connection of JAP

- **MixChannel encryption**
  - 1024 bit RSA/OAEP for asymmetric encryption
    - Note: the first Mix always use symmetric encryption instead of asymmetric one (keys exchange is done during connection of JAP)
  - AES-128-OFB for symmetric encryption
    - different keys for upstream / downstream are used
    - Remark: in the following slides only one key is shown
Anonymous Communication Channels

**Connection establishment**: initiated by the sender by sending a hybrid encrypted Channel-Open-Packet; establishes the MixChannel by giving each Mix a Channel-ID and two symmetric keys (for upstream / downstream).

**Data transmission**: sender and receiver transfer symmetric encrypted data packets.

<table>
<thead>
<tr>
<th>ID</th>
<th>M₁</th>
<th>M₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>id₁</td>
<td>k₁</td>
<td>k₂</td>
</tr>
<tr>
<td>id₂</td>
<td>k₃</td>
<td>k₆</td>
</tr>
<tr>
<td>id₃</td>
<td>k₄</td>
<td>k₇</td>
</tr>
<tr>
<td>id₄</td>
<td>k₅</td>
<td>k₈</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>in</th>
<th>Key</th>
<th>out</th>
</tr>
</thead>
<tbody>
<tr>
<td>id₁</td>
<td>k₁</td>
<td>id₂</td>
</tr>
<tr>
<td>id₂</td>
<td>k₃</td>
<td>id₄</td>
</tr>
<tr>
<td>id₃</td>
<td>k₄</td>
<td>id₆</td>
</tr>
<tr>
<td>id₅</td>
<td>k₅</td>
<td>id₈</td>
</tr>
</tbody>
</table>

**Channel-Open**

**Data (Upload)**

**Data (Download)**

more Up-/Download

Table of Channels
1. A MixPacket arrives
2. Link-Layer Decryption (Decryption of the first 16 Bytes using the Inter-Mix-Link key)
3. Decryption of the asymmetric encrypted part (first 128 bytes of the data part)
4. Decryption of the symmetric encrypted part using $k$
5. “left shift” of the data part and padding with random bits
6. Changing $ID$ to a new random $ID$
7. Link-Layer Encryption
1. A MixPacket arrives
2. Link-Layer Decryption (Decryption of the first 16 Bytes using the Inter-Mix-Link key)
3. Decryption of the asymmetric encrypted part (first 128 bytes of the data part)
4. Decryption of the symmetric encrypted part using $k$
5. “left shift” of the data part and padding with random bits
6. Changing $ID$ to a new random $ID'$
7. Link-Layer Encryption
First Lessons learned...

- **publish a specification!**
- set yourself a deadline for going public
  - otherwise you will never go public
- provide support for your „customers“
  - it helps you fixing bugs etc.
  - it gives you insights about your users
  - it increase you user base
    - having a large user base is helpful for empirical studies / research
  - but it is expensive!
- think about minimal necessary configuration options
  - users will change all settings – no matter how you warn them
  - provide “factory reset”
- (auto)update mechanisms are helpful
  - including: enforced update
  - notifications are helpful as well
- some users are demanding
  - even if everything is free of charge
Design of the anonymisation service AN.ON

Experiences: Usage and Misuse

Legal Framework

Implementation of Data Retention

Consequences of Data Retention
free of charge usable since September 2000

> 1,000,000 Downloads of JAP

Usage

estimated:

> 150,000 regular Users

> 5,000 User logged-in simultaneously

each Month:

> 18,75 TByte traffic

> 800 Million URLs
### Misuse of AN.ON

#### per Month:
- 2–4 requests from law enforcement agencies
- 3–6 requests from private persons / companies

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Law Enforcement Agencies</th>
<th>Private Persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>13</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>2002</td>
<td>40</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>2003</td>
<td>58</td>
<td>21</td>
<td>37</td>
</tr>
<tr>
<td>2004</td>
<td>61</td>
<td>38</td>
<td>23</td>
</tr>
<tr>
<td>2005</td>
<td>42</td>
<td>27</td>
<td>15</td>
</tr>
</tbody>
</table>
Abuse related requests (1st January 2004–30th June 2004)

- in total: 32 Requests
- 22 Requests from German Law Enforcement Agencies (mostly Police but also from public Prosecutors or Judges)
  - Requests are related to penal preliminary suspicions
  - 14 x Frauds (3 x eBay)
  - 5 x Libel
- 10 Requests from individuals or firms
  - Spam-Email
  - Frauds
  - Copyright violations
  - Hacking of Websites (stolen eBay passwords)
How to prevent Misuse?

- **Limitation of supported protocols/capabilities**
  - no communication with high “abuse potential” like plain TCP/IP
    - implemented, but deactivated
  - only HTTP (Web)
  - only well known HTTP ports (80, 443, 8080)
  - limited size of POST-requests (uploads)

- A webmaster can ask us to block access to his web site

- Prevention of Misuse in general is not possible
  - things lawful in one country may be unlawful in another one
  - Machines are not able to decide whether a certain request is “good” or “bad”
Police Department XY

Preliminary proceedings related to credit card fraud

10. October 2010

Dear ...,
regarding the preliminary proceedings mentioned above we investigate that the offender used the following IP addresses, belonging to your domain:

IP-address: 141.76.1.121          Date/Time: 05/26/2008, 09:05:46

You are asked for all data related to the given IP address and timestamp. ...

... The projects purpose is to enable the anonymous use of the Internet according to the specifications of the Teleservices Data Protection Act, § 4 IV. The general aim is to help to provide the possibility of anonymous and unobservable web access.
In order to realise this aim on a technical level the allocation of IP-addresses to individual users or to other identifying features is avoided. For this reason there are no logs available which could be retained or from which information could be taken. So we don't have any information regarding users at all. ...
Pls send me any adress to download because site close in our country

Discussion Forums: Help for JAP

By: Nobody/Anonymous - nobody

Located in China, cannot connect
2004-05-29 22:30

How has Jap tested in China? I am currently unable to connect to any mixes nor the info service. I am running the newest version of JAP, using a dialup connection, and have already configured the setting as according to JAP website(127.0.0.1) and have even tried forcing usage of an anon proxy. So far, I have gotten "error -6" could not connecto to mix every time. Any other users in China that have gotten JAP to work?
Censorship Scenario

Blockee

Blocker

“Free” Internet
JAP Forwarding Protocol

Because a censor blocks the access to the entire Internet and all available Mix cascades, JAP$_B$ connects to the AN.ON network via JAP$_R$. JAP$_R$ will forward requests from JAP$_B$ to a Mix cascade selected by JAP$_B$. Even the response is redirected to JAP$_B$ transparently.

JAP$_R$ reroutes the communication data between JAP$_B$ and a Mix cascade transparently.

- Mix packets of JAP$_B$
- Mix packets of JAP$_R$
Main idea: use Skype for data transmission JAP ↔ First Mix
How effective is censorship in the real world?

“Saudi Arabia is one of the countries that censors the Internet the most... Only China had so far used such an extreme measure to censor the Internet.” [Reporters without Borders]
✓ Design of the anonymisation service AN.ON

✓ Experiences: Usage and Misuse

► Legal Framework

Implementation of Data Retention

Consequences of Data Retention
AN.ON Law Enforcement

Mix 1  Mix 2  Mix 3
3rd July 2003: Judicial instruction given by the Lower District Court Frankfurt/Main

- concrete preliminary criminal proceedings by the German Federal Office of Criminal Investigation (BKA)
- §§ 100g, 100h Code of Criminal Procedure
- Retention / Information of communications with a given destination IP
- ULD appeals the decision — no postpone effect

Implementation / Activation of a “deanonymising function”

- noticed by the public, because AN.ON is Open Source
- published through press (news papers, Internet etc.)
- Result: one record

11th July 2003: District Court Frankfurt/Main suspended the judicial instruction

- Notification of ULD: 26th August 2003
- Final decision: 15th September 2003
- “no legal ground” for the request by the BKA
29th August 2003: Search warrant for the rooms of the AN.ON project given by the Lower District Court Frankfurt/Main
- on request of the BKA
- BKA „visits“ the director of the computer lab at home
- Duty to disclose information was already suspended
- Record was send via encrypted E-Mail to a police officer (encryption forced by AN.ON)

15th September 2003: District Court Frankfurt/Main confirms legal claim of AN.ON
- Request to record communication was unlawful

21st October 2003: District Court Frankfurt/Main again confirms claim of AN.ON
- Search warrant and confiscation of record were unlawful

ULD asked BKA and involved prosecuting authority to delete the record
- 22nd January 2004: BKA stated, that the record was send only to the local Saxon police
- 23rd March 2004: The local Saxon police stated, that the record was send only to the BKA
Data Retention in the EU

regulated by: "DIRECTIVE 2006/24/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 March 2006 on the retention of data generated or processed in connection with the provision of publicly available electronic communications services or of public communications networks and amending Directive 2002/58/EC"

purpose: "retention of certain data ..., in order to ensure that the data are available for the purpose of the investigation, detection and prosecution of serious crime, as defined by each Member State in its national law"

data to retain: "traffic and location data ... to identify ... registered user ... not ... the content of electronic communications, including information consulted using an electronic communications network."

Retention period: "not less than six months and not more than two years from the date of the communication"

access to retained data: "only ... competent national authorities in specific cases and in accordance with national law"
Article 5 of the Directive regulates in detail for each type of telecommunication service which data has to be retained.

“(2) No data revealing the content of the communication may be retained pursuant to this Directive.”
Data Retention in Germany

- Ruled by: “Act to reorganise Telecommunications observation and other undercover investigations and to implement the directive 2006/24/EC” (21st of December 2007) [Note: non official translation]

- Into force since: 1st of January 2008 (except Internet-based services: 1st of January 2009)
  - Appeal at Federal Constitutional Court: 34,000 suitors
  - Preliminary decision: restrictions on usage of retained data
  - Final decision (2nd March 2010): law is unconstitutional, but data retention is possible in principle

- new: § 113a Telecommunications Act — Obligation to retain data
  - (1) Those, who provide publicly available telecommunication services for end users has to store traffic data according to section 2 to 5, for six months within Germany or another member state of the European Union.

  - (6) Those, who provide telecommunication services and thereby alter data which have to be stored according to this law, have to store the original data and the new data as well as the time of the alteration.
Design of AN.ON

Experiences: Usage and Misuse

Legal Framework

Implementation of Data Retention

Consequences of Data Retention
Application of the Data Retention Rules on AN.ON

According to section 6 of § 113a TKG one has to store the modification of IP addresses. Therefore presumably:

- date and time of replacing of $IP_A$ resp. $IP_B$ by $IP_{OUT}$

**Problem:** many users “share” $IP_{OUT}$, therefore ambiguous backtracking can occur
Number of users logged in (red) or having an open channel (blue)

- Users logged-in
- active Users

Date

Number of Users

29.04.2008
01.05.2008
03.05.2008
05.05.2008
around 10 written requests from law enforcement agencies which were related to retained data
- some had formal errors, e.g. referred to the wrong paragraphs etc.
- none of the requests fulfilled the requirement of a court order
  - this in turn is related to the need for a (serious) crime listened in a special catalogue of crimes

around 10 telephone calls from law enforcement agencies asking for retained data
- again requirement of court order was not accomplishable
- additionally: expected set of suspicious IP-addresses ("at least 400") not helpful
  - according to a policemen from German Federal Criminal Office (BKA) even 5 IP-addresses are too much
    - no chance of getting a search warrant

Summary: no revealing of retained data until now
AN.ON-Next: Anonymity Online Next Generation

- [ ] Lightweight protection by the ISP
  - „zero-conf“ by user
- [ ] Enhanced protection against strong attackers
  - overlay based approach
  - current developments: Android client for AN.ON
- [ ] Privacy in 5G Networks
  - communication & location privacy
- [ ] OpenANON Library
  - common API for anonymous communication services
- [ ] Law & Regulation
  - balancing law enforcement ↔ anonymity
- [ ] Business models & Standardisation
  - sustainability...
Current research questions

※ How to effectively do mixing in case of data streams?
  ▶ state-of-the-art focuses on single mix packets only

※ How to implement dummy traffic?
  ▶ prevent attacks like:
    ☐ traffic conformation
    ☐ fingerprinting
  ▶ consider the overhead / costs
  ▶ SoA: either it does not help or it is to costly

※ How to prevent long term intersection attacks?

※ Is there a meaningful combination of client/server-based and P2P-based anonymization?
  ▶ extended attacker model
  ▶ better anonymization
  ▶ better performance
  ▶ less overhead
Questions?

Good work, but I think we might need just a little more detail right here.
Radio networks (1)

Difference to wired networks
• Bandwidth of transmission remains scarce
• The current place of the user is also to be protected

Assumptions
• Mobile user station is *always* identifiable and locatable if the station sends.
• Mobile user station is *not* identifiable and locatable if the station only (passively) receives.

Which measures are applicable?
+ end-to-end encryption
+ link encryption
- dummy messages, unobservability of neighboring lines and stations as well digital signal regeneration, superposed sending

→ all measures to protect traffic data and data on interests have to be handled in the wired part of the communication network
+ Broadcast the call request in the whole radio network, only then the mobile station answers. After this the transmission proceeds in one radio cell only.

+ Filter + Generation of visible implicit addresses + Restrict the region

+ Keep the user and SIM anonymous towards the mobile station used.

if the coding in the radio network is different or computing power for encryption is missing
No movement profiles in radio networks

GSM/UMTS – cellular mobile networks

• roaming information in central data bases
• operators of the network can record the information

Alternative concept

• Maintenance of the roaming information in a domain of trust
  - at home (HPC)
  - at trustworthy organizations
• Protection of the communication relationship using MIXes
• Use Case:
  – Location-aware Apps

• Assumptions:
  – untrusted Apps are interested in location inside a defined geographic region (*application zone*)
  – trusted middleware

• Idea:
  – middleware reveals location using App-specific user pseudonyms

• Problem:
  – colluding Apps

• Solution:
  – Mix Zones: no location tracing at all
Mix Zones: User Privacy in Location-aware Services

[Alastair R. Beresford, Frank Stajano, 2004]

- Timing information!
Using the network transactions between anonymous partners explicit proof of identity is possible at any time

Protection of traffic data and data on interests requires appropriate network structure keep options consider early enough

Networks offering anonymity can be operated in a “trace users mode” without huge losses in performance, the converse is not true!
Trustworthy data protection in general or only at individual payment for interested persons?

- Concerning traffic data, the latter is technically inefficient.
- The latter has the contrary effect (suspicion).
- Everyone should be able to afford fundamental rights!
Electronic Banking

Motivation

- **Banking using paper forms – premium version**
  Customer gets the completely personalized forms from the bank in which only the value has to be filled in. No signature!

- **Electronic banking – usual version**
  Customer gets card and PIN, TAN from his/her bank.
  [http://www.cl.cam.ac.uk/research/security/banking/](http://www.cl.cam.ac.uk/research/security/banking/)

Upcoming / Current

- Customer gets chip card from Bank with
  - key for MAC
  - key pair for digital signature

- Map exercise of US secret services: observe the citizens of the USSR (1971, Foy 75)

Main part (Everything a little bit more precise)

- Payment system is secure ...
  - MAC, digital signature
  - payment system using digital signatures

- Pseudonyms (person identifier ↔ role-relationship pseudonyms)
Chip & PIN Problem

Verify PIN

PIN ok
Chip & PIN Problem

Verify PIN

Verified by Signature

Signed Transaction Record

PIN ok
Security properties of digital payment systems

digital (integrity, availability)

Payment system is **secure** if

- user can transfer the rights received,
- user can lose a right only if he is willing to,
- if a user who is willing to pay uniquely denotes another user as recipient, only this entity receives the right,
- user can prove transfers of rights to a third party if necessary (receipt problem), and
- the users cannot increase their rights even if they collaborate,

without the committer being identified.

Problem: messages can be copied perfectly
Solution: witness accepts only the *first* (copy of a) message
Scalability concerning the protection of anonymity
Distinction between:

1. **Initial linking** between the pseudonym and its holder

2. Linkability due to the **use** of the pseudonym **across** different contexts
Pseudonyms: Initial linking to holder

Public pseudonym:
The linking between pseudonym and its holder may be publicly known from the very beginning.

Phone number with its owner listed in public directories

Initially non-public pseudonym:
The linking between pseudonym and its holder may be known by certain parties (trustees for identity), but is not public at least initially.

Bank account with bank as trustee for identity,
Credit card number ...

Initially unlinked pseudonym:
The linking between pseudonym and its holder is – at least initially – not known to anybody (except the holder).

Biometric characteristics; DNA (as long as no registers)
Pseudonyms: Use across different contexts => partial order

A → B stands for “B enables stronger unlinkability than A”
Notations: transfer of a signed message from $X$ to $Y$

**functional notation**

- signing the message $M$: $s_A(M)$

**graphical notation**

- test the signature: $t_A(M, s_A(M))$?
Authenticated anonymous declarations between business partners that can be de-anonymized

trusted third party $A$

identification

user $X$

document for $p_G(X, g)$

confirmation

know $p_G(X, g)$

$p_A$

trusted third party $B$

identification

user $Y$

document for $p_G(Y, g)$

confirmation

know $p_G(Y, g)$

$p_B$

Generalization:

$X \rightarrow B_1 \rightarrow B_2 \rightarrow \ldots \rightarrow B_n \rightarrow Y$

$B'_1 \rightarrow B'_2 \rightarrow \ldots \rightarrow B'_m$

error / attack tolerance (cf. MIXes)
Authenticated anonymous declarations between business partners that can be de-anonymized

trusted third party A

identification

user X

trusted third party B

identification

user Y

trustees for identities

Generalization:

\[ X \rightarrow B_1 \rightarrow B_2 \rightarrow \ldots \rightarrow B_n \rightarrow Y \]

\[ B'_1 \rightarrow B'_2 \rightarrow \ldots \rightarrow B'_m \]

error / attack tolerance (cf. MIXes)
Security for completely anonymous business partners using active trustee who can check the goods

[1] order
merchant is
\( p_L(Y,g) \) + "money" for merchant

[4] delivery to customer
delivery to customer
checked by \( T \)

[3] delivery to trustee
delivery to trustee

[2] order of the customer
(order is deposited)

[5] money
money

\( p_K(X,g) \)

\( p_T \)

\( p_T \)

\( p_T \)

\( p_T \)
Security for completely anonymous business partners using active trustee who can not check the goods

1. Order delivery is \( p_L(Y, g) \) + "money" for distributor

2. Money deposited

3. Delivery to trustee

4. Delivery to customer

5. Money

\[ p_T(\text{money}) \]
Security for completely anonymous business partners using active trustee who can (not) check the goods

trustee for values

[1] order
delivery is \( p_L(Y, g) \) + „money“ for distributor

\[ p_K(X, g) \]

[2] order of the customer
(money is deposited)

[3] delivery to trustee

\( p_L(Y, g) \)

[4] delivery to customer

checked by

[5] money

customer \( X \)

merchant \( Y \)
Anonymously transferable standard values

current owner:
  digital pseudonym

value number: $v_n$

10 $ 

former owners

- digital pseudonym 1, transfer order 1
- digital pseudonym 2, transfer order 2
- digital pseudonym 3, transfer order 3

.....
• Key feature: Bitcoin transfer between pseudonyms (Bitcoin addresses)
• Bitcoin pseudonym ≡ public key of ECDSA
• Sender signs transfer
• Double spending protection:
  – Bitcoin network keeps history of all transactions
  – Transactions have timestamps → only oldest is valid
    • Bitcoin network works as “distributed time server”
  – Binding of transaction and timestamp: „proof-of-work“:
    • search for $z$: $\text{Hash}(\text{Transaction}, \text{Timestamp}, z) = 00000… (0|1)^* < w$
    • $w$ adjusted over timer
• https://www.blockchain.info
Basic scheme of a secure and anonymous digital payment system

1. Choice of pseudonyms
   - $p_z(X,t) = p_z^B(X,t)$
   - $p_E(Y,t) = p_E^B(Y,t)$

2. Transfer order of the payer
   - $p_E^B(Y,t)$ owns the right, got from $p_z^B(X,t)$
   - $p_z^B(X,t)$ owns the right

3. Authentication by the witness
   - $p_E^B(Y,t)$ have transferred the right to $p_E(Y,t)$.

4. Receipt for the payer
   - $p_z(X,t)$ have got the right from $p_z^B(X,t)$.

5. Authentication for the recipient
   - $p_z(X,t)$ have transferred the right to $p_E(Y,t)$.
Transformation of the authentication by the witness

[1] choice of pseudonyms
\[ p_{E}(Y,t) \approx p_{E}(Y,t) \]
\[ p_{Z}(X,t) \approx p_{Z}(X,t) \]

[2] transfer order of the payer
\[ p_{Z}^{B}(X,t) \] owns the right
\[ \text{transfer the right to } p_{E}^{B}(Y,t) \]

[3] authentication by the witness
\[ p_{E}^{B}(Y,t) \] owns the right, got from \[ p_{Z}^{B}(X,t) \]

[4] receipt for the payer
\[ \text{have got the right from } p_{Z}(X,t) \]
\[ p_{E}(Y,t) \]

[5] authentication for the recipient
\[ \text{have transferred the right to } p_{E}(Y,t) \]
\[ p_{Z}(X,t) \]

[6] \[ p_{Z}^{B}(Y,t+1) \]
\[ \text{owns the right} \]

payer X

recipient Y

witness B
Transformation of the authentication by the witness:

Simplified Steps

1. \( p_B \);
2. \( EUR 10 \);
3. \( EUR 10 \);
4. \( EUR 10 \).

- \( p_B \).
- \( recipient~Z \).
- \( payer~Y \).
- \( witness~B \).
Transformation of the authentication by the witness

1. **Choice of pseudonyms**
   - \( p_E(Y,t) \approx p_E(Y,t) \)
   - \( p_Z(X,t) \approx p_Z(X,t) \)

2. **Transfer order of the payer**
   - \( p_Z^B(X,t) \) owns the right
   - \( p_B \) have transferred the right to \( p_E^B(Y,t) \)

3. **Authentication by the witness**
   - \( p_E^B(Y,t) \) owns the right, got from \( p_Z^B(X,t) \)

4. **Receipt for the payer**
   - \( p_B \) have got the right from \( p_Z(X,t) \)

5. **Authentication for the recipient**
   - \( p_Z(X,t) \) have transferred the right to \( p_E(Y,t) \)

6. **Recruitment of the right**
   - \( p_Z^B(Y,t+1) \) owns the right
The next round: Y in the role payer to recipient Z

1. Choice of pseudonyms:
   - \( p_E(Z,t+1) \approx p_E^B(Z,t+1) \)
   - \( p_Z(Y,t+1) \approx p_Z^B(Y,t+1) \)

2. Transfer order of the payer:
   - \( p_Z^B(Y,t+1) \) owns the right
   - \( p_Z(Y,t+1) \) transfers the right to \( p_E^B(Z,t+1) \)

3. Authentication by the witness:
   - \( p_E^B(Z,t+1) \) owns the right, got from \( p_Z^B(Y,t+1) \)

4. Receipt for the payer:
   - \( p_E(Z,t+1) \) have got the right from \( p_Z(Y,t+1) \)

5. Authentication for the recipient:
   - \( p_Z(Y,t+1) \) have transferred the right to \( p_E(Z,t+1) \)

6. Authentication of ownership:
   - \( p_Z^B(Y,t+1) \) owns the right

Payer Y

Recipient Z
Signature system for signing blindly

Key generation

Key for testing of signature, publicly known

Random number

Key for signing, kept secret

Text

Random number \( z' \)

Blind

Text with signature and test result

\( x, s(x), \) "pass" or "fail"

Unblind and test

Blinded text

\( z'(x) \)

Signing

Blinded text with signature

\( z'(x), s(z'(x)) \)

"Pass" or "fail"
RSA as digital signature system with collision-resistant hash function \( h \)

**Key Generation:**

- \( p, q \) prime numbers
- \( n := p \cdot q \)
- \( t \) with \( \gcd(t, (p-1)(q-1)) = 1 \)
- \( s \equiv t^{-1} \mod (p-1)(q-1) \)

**Key for Testing of Signature:**

- Publicly known \( t, n \)

**Key for Signing:**

- Kept secret \( s, n \)

**Test:**

- \( x, (h(x))^s \mod n \)
- "pass" or "fail"

**Signing:**

- Text with signature \( x, (h(x))^s \mod n \)
- \( (h(\cdot))^s \mod n \)
One time convertible authentication

**Recipient**

choose pseudonym\n
\[ p \]

(test key of arbitrary sign. system)

Collision-resistant hash function \( h \)

\[ p, h(p) \]

choose \( r \in \mathbb{Z}_n^* \)

\[ (p, h(p)) \cdot r^t \]

\[ (p, h(p))^s \cdot r \]

multiply with \( r^{-1} \)

get \( (p, h(p))^s \)

**Issuer (i.e. witness)**

RSA test key \( t,n \), publicly known

\[ ((p, h(p)) \cdot r^t)^s \]
Secure device: 1st possibility

[1] choice of pseudonyms
\[ p_{E}(Y,t) \approx p_{E}^{B}(Y,t) \]
\[ p_{Z}(X,t) \approx p_{Z}^{B}(X,t) \]

[2] transfer order of the payer
\[ p_{Z}^{B}(X,t) \] owns the right to \[ p_{E}^{B}(Y,t) \]

[3] authentication by the witness
\[ p_{E}^{B}(Y,t) \] owns the right, got from \[ p_{Z}^{B}(X,t) \]

[4] receipt for the payer
\[ p_{E}(Y,t) \] have got the right from \[ p_{Z}(X,t) \]

[5] authentication for the recipient
\[ p_{E}(Y,t) \] have transferred the right to \[ p_{E}(Y,t) \]

payer X

witness B

as secure device

recipient Y
Secure device: 2\textsuperscript{nd} possibility

1. Choice of pseudonyms
   - \( p_E(Y,t) = p_E^B(Y,t) \)
   - \( p_Z(X,t) = p_Z^B(X,t) \)

2. Transfer order of the payer
   - \( p_Z^B(X,t) \) owns the right
   - \( p_E^B(Y,t) \) owns the right, got from \( p_Z^B(X,t) \)

3. Authentication by the witness
   - \( p_E^B(Y,t) \) owns the right, got from \( p_Z^B(X,t) \)

4. Receipt for the payer
   - \( p_E^B(Y,t) \) have got the right from \( p_Z^B(X,t) \)

5. Authentication for the recipient
   - \( p_Z^B(X,t) \) have transferred the right to \( p_E^B(Y,t) \)
   - \( p_Z(X,t) \) have got the right from \( p_Z^B(X,t) \)

Symmetric encryption system suffices
Offline payment system

Payment systems with security by Deanonymizability

$k$ security parameter

$l$ identity of the entity giving out the banknote

$r_i$ randomly chosen ($1 \leq i \leq k$)

$C$ commitment scheme with information theoretic secrecy

blindly signed banknote:

$$s_{\text{Bank}}(C(r_1), C(r_1 \oplus l), C(r_2), C(r_2 \oplus l), \ldots, C(r_k), C(r_k \oplus l)),$$

recipient decides, whether he wants to get revealed $r_i$ or $r_i \oplus l$.

(one-time pad preserves anonymity.)

Hand-over to two honest recipients:

probability ($\exists i :$ bank gets to know $r_i$ and $r_i \oplus i$) $\geq 1-e^{-c \cdot k}$

(original owner identifiable)
Secure and anonymous digit. payment system with accounts
845 authorizes A:

A notifies 845:

845 pays B €

B certifies 845:

C pays 845 €
Role pseudonyms
(business-relationship and transaction pseudonyms)
 Usually: one identity per user

Problem: **Linkability** of records
Many Partial-Identities per user

* Management / disclosure / linkability under the control of the user
• many services need only a **few data**

• revealing that data under a **Pseudonym** prevents unnecessary linkability with other data of the user

• **different actions / data** are initially unlinkable if one uses different pseudonyms

---

**Example: Car Rental**

necessary data:
- Possession of a driving license valid for the car wanted
Anonymous Credentials

- **Credential** = Attestation of an attribute of a user (e.g. “User has driving license”)

**Steps:**
- Organisation issues credentials
- User shows credential to service provider

**Properties:**
- User can show credentials under different pseudonyms (transformation)
- Usage of the same credential with different pseudonyms prevents linkability against the service provider and the issuer.
Usage of Anonymous Credentials

User A has driving-license

Credentials issuing Organisation

User A has driving-license

Service provider

User B has driving-license

User X has driving-license
Data Publishing – Use-Case

Collection → Anonymization → Publishing

...
Data Publishing – Classification of Data

- Explicit identifiers must be removed
- Link between **Quasi-IDs** and sensitive attributes needs to be obfuscated

<table>
<thead>
<tr>
<th>Quasi ID</th>
<th>Sensitive</th>
<th>Non-sensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZIP</td>
<td>Age</td>
<td>Sex</td>
</tr>
<tr>
<td>47677</td>
<td>43</td>
<td>Male</td>
</tr>
<tr>
<td>47602</td>
<td>22</td>
<td>Female</td>
</tr>
<tr>
<td>47678</td>
<td>45</td>
<td>Female</td>
</tr>
<tr>
<td>47905</td>
<td>31</td>
<td>Male</td>
</tr>
<tr>
<td>47909</td>
<td>36</td>
<td>Male</td>
</tr>
</tbody>
</table>
Quasi-IDs: an Example

- Re-identification through directly linking shared attributes

- 87% of US population show characteristics to be uniquely identifiable through \{ZIP, Date of birth, Sex\} (Census 1990)

Data Publishing – Classification of Data

- Explicit identifiers must be removed
- Link between Quasi-IDs and sensitive attributes needs to be obfuscated
  - Generalization & Suppression
  - Anatomization & Permutation
  - Perturbation

<table>
<thead>
<tr>
<th>Quasi ID</th>
<th>Sensitive</th>
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</tr>
</thead>
<tbody>
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<td>Female</td>
</tr>
<tr>
<td>47905</td>
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<td>Male</td>
</tr>
<tr>
<td>47909</td>
<td>36</td>
<td>Male</td>
</tr>
</tbody>
</table>
Data Publishing – Anonymization (\(k\)-Anonymity)

- Groups of \(k\) records \(\rightarrow\) resulting in \(k\)-anonymous table
- Probability \(1/k\) to link correct entry to known quasi-identifier
- Tradeoff between privacy and utility
  - larger groups normally result in less accurate data
- Problem: Homogeneity in sensitive attributes
  - Solution: \(l\)-diversity \(\rightarrow\) at least \(l\) different values for each sensitive attribute in each equivalence class
  - Problem: meaning of “different”: different kinds of cancer \(\rightarrow\) cancer
    - Solution: \(t\)-closeness

<table>
<thead>
<tr>
<th>ZIP Code</th>
<th>Age</th>
<th>Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47677</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>2</td>
<td>47602</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>3</td>
<td>47678</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>4</td>
<td>47905</td>
<td>Flu</td>
</tr>
<tr>
<td>5</td>
<td>47909</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>6</td>
<td>47906</td>
<td>Cancer</td>
</tr>
</tbody>
</table>

\(k=3\)

<table>
<thead>
<tr>
<th>ZIP Code</th>
<th>Age</th>
<th>Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>476**</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>2</td>
<td>476**</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>3</td>
<td>476**</td>
<td>Heart Disease</td>
</tr>
<tr>
<td>4</td>
<td>4790*</td>
<td>(\geq 40) Flu</td>
</tr>
<tr>
<td>5</td>
<td>4790*</td>
<td>(\geq 40) Heart Disease</td>
</tr>
<tr>
<td>6</td>
<td>4790*</td>
<td>(\geq 40) Cancer</td>
</tr>
</tbody>
</table>
Privacy-Preserving Data Mining

- Secure Computations
  - min. 2 parties
  - distributed inputs or outsourced computations
  - different requirements
  - no single point of trust
  - protocol design

- **Secure string matching**
  - sequence comparisons
  - similarity between strings
  - fuzzy text search
  - basis for text mining
Privacy-Preserving Data Mining
Secure Multi-Party Computations

Secret Sharing
Secure Computation
Result Delivery
Privacy-Preserving Data Mining
Homomorphic Encryption

1. Encryption

2. Crypted Processing

3. Decrypting Result
Computation with secret inputs

- inputs could be from different parties

- Based on the properties of a Homomorphism:
  \[ f(a) \circ f(b) = f(a+b) \]

- in principle: arbitrary "circuits" / algorithms computable
  - huge overhead!

Secure Computation—
Homomorphic Encryption

Computation e.g. in the Cloud

\[ E(a) \ast E(b) = E(a+b) \]
Cryptography and the impossibility of its legal regulation

- Cryptography *(you already know)*
- Steganography
- Proposals to regulate cryptography
- Technical limits of regulating cryptography
  - Secure digital signatures → Secure encryption
  - Key Escrow encryption without permanent surveillance → Encryption without Key Escrow
  - Symmetric authentication → Encryption
  - Multimedia communication → Steganography
  - Keys for communication and secret signature keys can be replaced at any time → Key Escrow to backup keys is nonsense
- Proposals to regulate cryptography harm the good guys only
Steganography

cover  cover*
emb  emb

<table>
<thead>
<tr>
<th>secret message</th>
<th>secret message</th>
</tr>
</thead>
</table>

sender  attacker

embedding  extracting
Steganography

Domain of trust

Sender

Secret message

Embedding

Stegotext

Attacker

Area of attack

Recipient

Secret message

Extracting

Cover

Cover*

Emb
Steganography: Secrecy of secrecy

- exactly the same
- cannot be detected
- as much as possible
- no changes

sender -> embedding
emb
secret message

attacker

stegotext

key

recipient

extracting

cover*

emb
secret message
Steganography: Watermarking and Fingerprinting

- correlation is enough
- some 100 bit are enough
Proposals to regulate cryptography?

- Would you regulate cryptography to help fight crime?
- If so: How?
Proposals to regulate cryptography!

- Outlaw encryption
- Outlaw encryption – with the exception of small key lengths
- Outlaw encryption – with the exception of Key Escrow or Key Recovery systems
- Publish public encryption keys only within PKI if corresponding secret key is escrowed
- Obligation to hand over decryption key to law enforcement during legal investigation
Secure digital signatures $\rightarrow$ Secure encryption

1. $t_A$
2. $t$ of $A$
3. $s_{CA}(A,t_A)$

- **A**
  - generates $(s_A, t_A)$
  - generates $(c_A, d_A)$

- **B**
  - test CA-certificate
  - test A-certificate

$c_A$ (secret message)

A does not need a certificate for $c_A$ issues by CA

$s_A(A, c_A)$
Key Escrow encryption without permanent surveillance

\[ k_{esc}(A, c_A) \]

\[ c_A \text{(secret message)} \]

\[ \rightarrow \text{Encryption without Key Escrow} \]
Key Escrow encryption without permanent surveillance

A \xrightarrow{k_{esc}(A,c_A)} \rightarrow B

k_{esc}(c_A(\text{secret message}))

employ Key Escrow additionally to keep your encryption without Key Escrow secret
Key Escrow encryption without permanent surveillance

$k_{esc}(A, c_A)$

$k_{esc}(c_A(k_{AB}), k_{AB}(secret\ message))$

hybrid encryption can be used
Key Escrow encryption without permanent surveillance

if surveillance is not done or even cannot be done retroactively, **symmetric encryption alone** does the job
Symmetric authentication → Encryption

Sender $A$
Kenn $k_{AB}$
Zu übertragen sei Nachricht $b_1, \ldots, b_n$ mit $b_i \in \{0, 1\}$
Berechnet
$MAC_1 := \text{code}(k_{AB}, b_1) \ldots MAC_n := \text{code}(k_{AB}, b_n)$

Sei $a_1, \ldots, a_n$ die bitweise invertierte Nachricht.
Wählt zufällig $MAC'_1 \ldots MAC'_n$ mit
$MAC'_1 \circ \text{code}(k_{AB}, a_1) \ldots MAC'_n \circ \text{code}(k_{AB}, a_n)$

Überträgt (die Mengenklammern bedeuten „zufällige Reihenfolge“)

$\{(b_1, MAC_1), (a_1, MAC'_1)\} \ldots$
$\{(b_n, MAC_n), (a_n, MAC'_n)\}$

Empfänger $B$
Kenn $k_{AB}$

falsely authenticated messages

intermingle

form

separate

Probiert, ob
$\{MAC_1 = \text{code}(k_{AB}, b_1)\}$ oder
$\{MAC'_1 = \text{code}(k_{AB}, a_1)\}$
und empfängt den passenden Wert $b_1$

... probiert, ob
$\{MAC_n = \text{code}(k_{AB}, b_n)\}$ oder
$\{MAC'_n = \text{code}(k_{AB}, a_n)\}$
und empfängt den passenden Wert $b_n$
Symmetric authentication → Encryption

Sender A

Kenn $k_{AB}$

Zu übertragen sei Nachricht $b_1, \ldots, b_n$ mit $b_i \in \{0, 1\}$

Berechnet

$MAC_1 := \text{code}(k_{AB}, b_1) \ldots MAC_n := \text{code}(k_{AB}, b_n)$

Überträgt

$(1, b_1, MAC_1), \ldots (n, b_n, MAC_n)$

Empfänger B

Kenn $k_{AB}$

Komplementgenerierer

Hört die Nachricht $b_1, \ldots, b_n$ ab.

Bildet $a_1, \ldots, a_n$, die bitweise invertierte Nachricht.

Wählt zufällig $MAC'_1, \ldots, MAC'_n$ und mischt in den Nachrichtenstrom von Sender A an die passenden Stellen

$(1, a_1, MAC'_1), \ldots (n, a_n, MAC'_n)$

Überträgt die Mischung

Abhörer

kann $a_i$ und $b_i$ nicht unterscheiden

falsely authenticated messages

form and intermingle

without knowing the key

normales Authentikationsprotokoll

Ignoriert Nachrichten mit falscher Seque

Ignoriert Nachrichten mit falscher Authe

gibt die übrigbleibenden weiter

empfangen wird mit größter Wahrschein

$b_1, \ldots, b_n$
Exchanging keys outside the communication network is easy for **small closed groups**, in particular it is easy for criminals and terrorists.

**Large open groups** need a method of key exchange which works without transmitting suspicious messages within the communication network – asymmetric encryption cannot be used directly for key exchange.

Solution:

**Diffie-Hellman Public-Key Agreement**

Uses public keys of a commonly used digital signature systems (DSS, developed and standardized by NSA and NIST, USA)
Key exchange without message exchange

Diffie-Hellman Public-Key Agreement

secret: $x$ \hspace{2cm} $y$

public: $g^x$ \hspace{2cm} $g^y$

$(g^y)^x = g^{yx} = g^{xy} = (g^x)^y$
Key exchange for steganography!

Diffie-Hellman Public-Key Agreement

secret: \( x \quad y \)

public: \( g^x \quad g^y \)

\((g^y)^x = g^{yx} = g^{xy} = (g^x)^y\)

\[ f(C, g^{yx}) = f(S, g^{xy}) \]
Digital Signatures

Key Escrow without permanent surveillance

Multimedia communication

Summary

Encryption

Key exchange, multiple encryption

Steganography

Cryptoregulation ignores technical constraints
Exchanging new keys is more efficient and more secure than Key Recovery.

Key Recovery for communication is nonsense.

Communication

Authentication: generate new one(s) and exchange using CA

Encryption: generate new one(s) and exchange

Authenticate/encrypt and transmit message(s) once more

Long-term storage

Symmetric Authentication

Encryption

Dig. Signature: already generated digital signatures can still be tested; generate new key-pair for new digital signatures and, if you like, let certify your new public key

Key Recovery makes sense
<table>
<thead>
<tr>
<th>Encryption</th>
<th>protecting communication</th>
<th>protecting long-term storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authentication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>symmetric (MACs)</td>
<td>Key Recovery functionally unnecessary, but additional security risk</td>
<td>Key Recovery useful</td>
</tr>
<tr>
<td>asymmetric (dig. signature)</td>
<td>Key Recovery</td>
<td></td>
</tr>
</tbody>
</table>
Proposals to regulate cryptography harm the good guys only

- Outlaw encryption
- Outlaw encryption – with the exception of small key lengths
- Outlaw encryption – with the exception of Key Escrow or Key Recovery systems
- Publish public encryption keys only within PKI if corresponding secret key is escrowed
- Obligation to hand over decryption key to law enforcement during legal investigation

- Steganography
- In addition steganography
- Use Key Escrow or Key Recovery system for bootstrap
- Run PKI for your public encryption keys yourself
- Calculate one-time-pad accordingly
(Im-)Possibility to regulate anonymous/pseudonymous communication

• Explicit techniques (you already know the theory)

• Workarounds
Anon-Proxies

MIXes

Cascade: AN.ON

P2P: TOR

All this exists abroad without regulation – as long as we do not have a global home policy
(Im-)Possibility to regulate anonymous/pseudonymous communication

But even domestic:

- Public phones,
- Prepaid phones,
- Open unprotected WLANs,
- Insecure Bluetooth mobile phones,
- ...

Data retention is nearly nonsense, since „criminals“ will use workarounds, cf. above
• 14.7. Martin Übung
• 16.7. Benjamin Kellerman „dudle“ – privacy preserving meeting scheduling based on DC-net ideas
• 21.7. Computation on encrypted data
• 23.7 Stefanie: “freenet – a privacy-preserving P2P system“
Group Signatures
(Chaum, van Heyst 1991)

• Idea: digital signature on behalf of a group without revealing which group member did sign

• Setting:
  – Group Manager (can be distributed):
    • generates group key pair
    • join / leave of group members
    • revoke anonymity of group members
  – Join:
    • member learns *his* private key for signing
  – Leave:
    • private key of the member is revoked
  – Signing:
    • every member of group
  – Verification:
    • everybody with the help of the group public key
Properties of a Group Signature Scheme

• Soundness and Completeness
  – valid signatures always verify correctly
  – invalid signatures always fail verification.

• Unforgeable
  – only group members can create valid signatures

• Anonymity
  – given a message and its signature, the signing group member cannot be determined without the group manager's private key

• Traceability
  – group manager can trace which group member issued a signature

• Unlinkability
  – given two messages and their signatures, only group manager can tell if the signatures were from the same signer or not
Properties of a Group Signature Scheme

• No Framing
  – colluding group members (and manager) cannot forge a signature of a non-participating group member

• Unforgeable tracing verification
  – group manager cannot falsely accuse a signer of creating a signature he did not create

• Coalition resistance
  – colluding group members cannot generate a signature that the group manager cannot trace to one of the colluding group members
Zero Knowledge Proof of Knowledge (ZKP)