Distributed Key Generation and Threshold Cryptography for OpenPGP

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Datengarten/81, October 2017, Berlin

Background

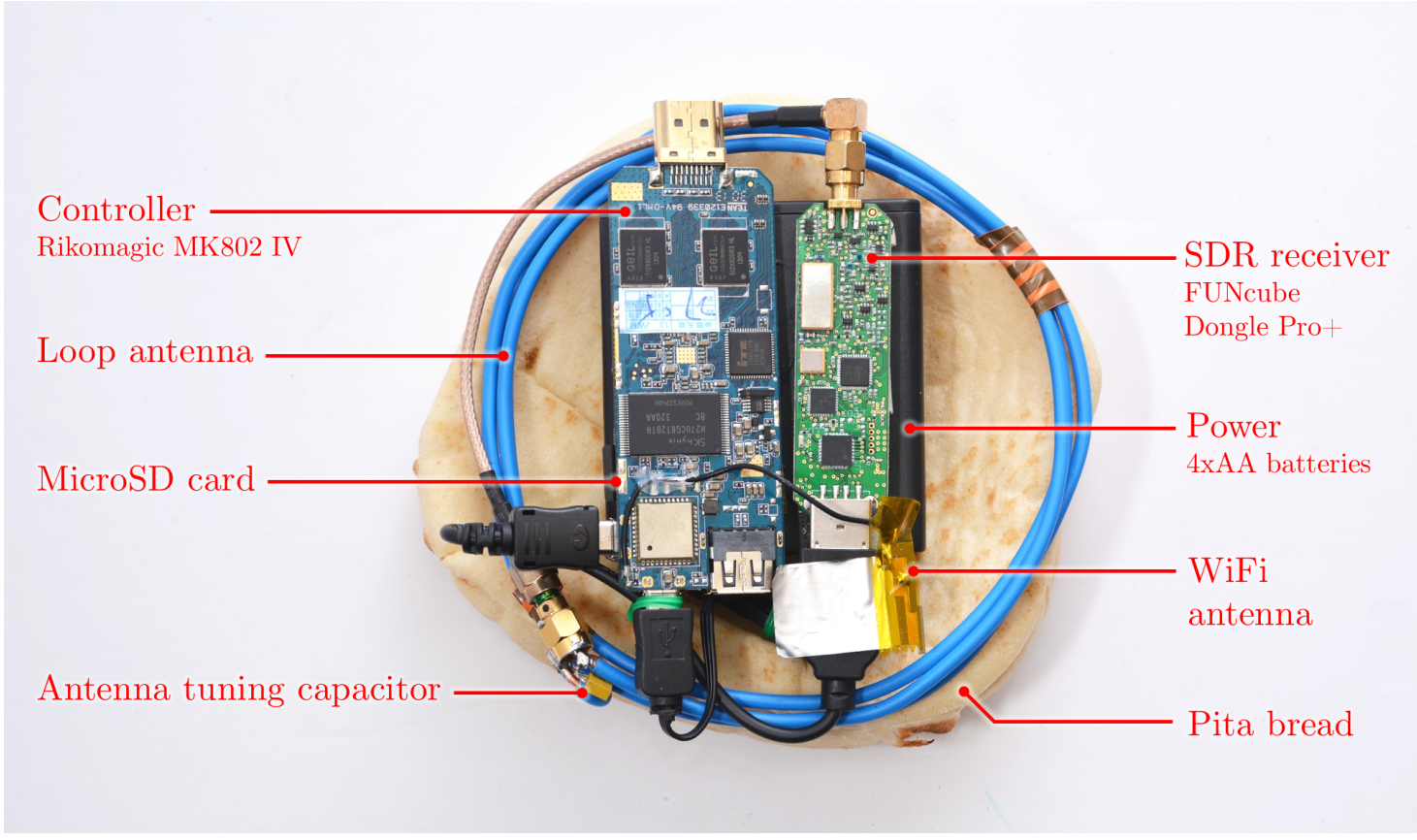
Source: Bruno Sanchez-Andrade Nuño, CC BY 2.0

Phillip Rogaway: *The Moral Character of Cryptographic Work*
`http://web.cs.ucdavis.edu/~rogaway/papers/moral.html`

> *We need to realize popular services in a secure, distributed, and decentralized way, powered by free software and free/open hardware.*

What is the problem?

Where is the problem?



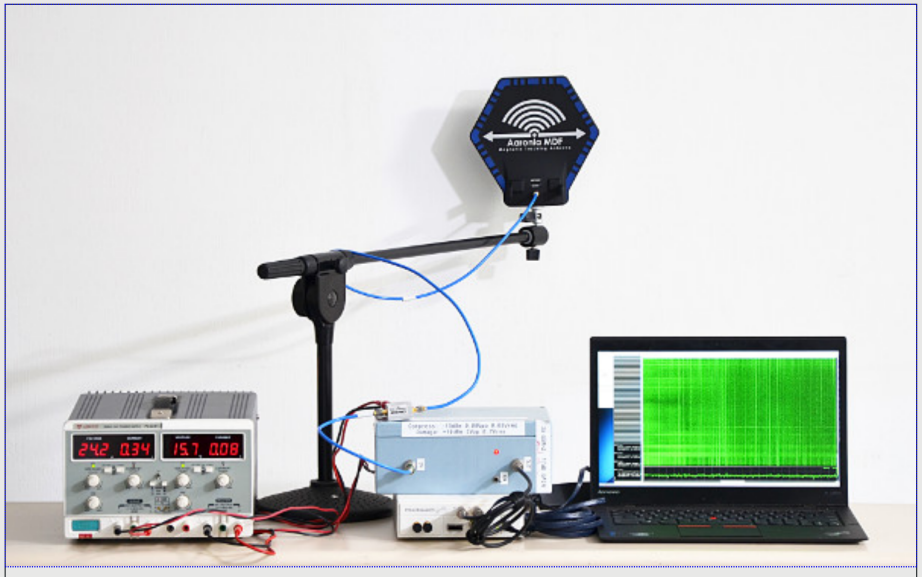
Daniel Genkin, Lev Pachmanov, Itamar Pipman, and Eran Tromer.
Stealing Keys from PCs using a Radio: Cheap Electromagnetic Attacks on Windowed Exponentiation. http://eprint.iacr.org/2015/170

Workshop on Cryptographic Hardware and Embedded Systems (CHES), 2015.

Vulnerable software: GnuPG $\leqslant$ 1.4.18, Libgcrypt $\leqslant$ 1.6.2 (CVE-2014-3591)

Where is the problem?

Better side-channel attacks on ECDH and ECDSA followed . . .



Attacker's setup for capturing EM emanations. Left to right: power supply, antenna on a stand, amplifiers, software defined radio (white box), analysis computer.

Target laptop performing ECDH decryption using its secret key , on the other side of the wall.

Daniel Genkin, Lev Pachmanov, Itamar Pipman, Eran Tromer.
ECDH key-extraction via low-bandwidth electromagnetic attacks on PCs.
`https://eprint.iacr.org/2016/129`
RSA Conference Cryptographers' Track (CT-RSA) 2016.
Costs: \$ 3000, Vulnerable software: Libgcrypt $\leqslant$ 1.6.3 (CVE-2015-7511)

Mitigation measures

Make side-channel attacks difficult

- Hardware: electromagnetic shielding or tamper-proof HSM
- Software: constant-time operations on secret key material

Splitting/Sharing of private keys

- Example ICANN/IANA: DNSSEC root zone signing key

  `https://www.cloudflare.com/dns/dnssec/root-signing-ceremony/`

  `https://www.iana.org/dnssec/ceremonies/`
- Example Debian GNU/Linux: FTP archive signing key

  `https://ftp-master.debian.org/keys.html`

  `http://www.digital-scurf.org/software/libgfshare`

  The program gfshare (package libgfshare-bin) (a Shamir's secret sharing scheme implementation) is used to produce 5 shares of which 3 are needed to recover the secret key.

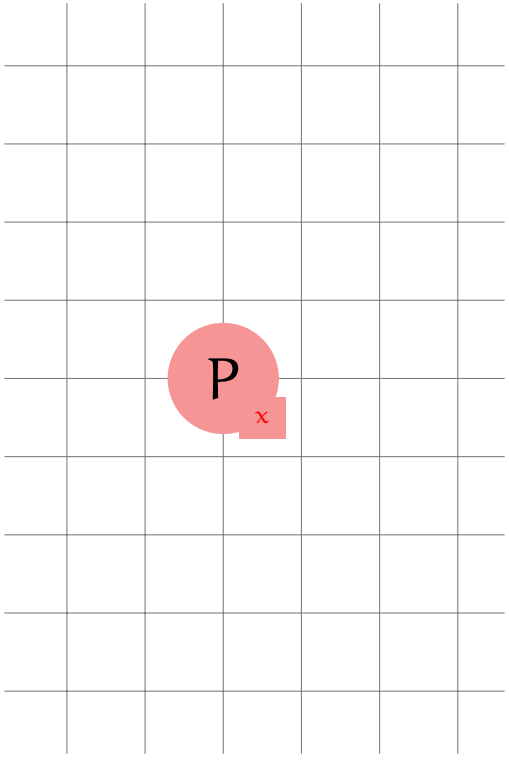
Problems: trusted hardware needed, more side-channels issues possible (e.g. CVE-2016-6316), no verifiable secret sharing (VSS)

Threshold Cryptography

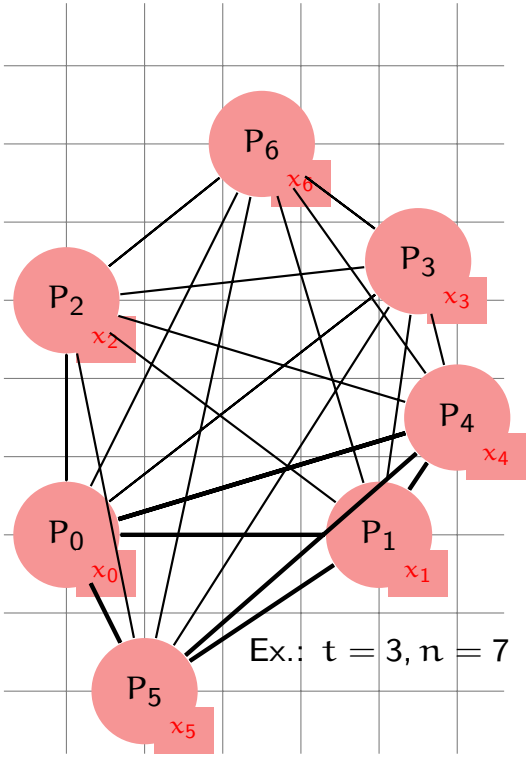
Boy86 Boyd: *Digital Multisignatures.* Cryptography and Coding, 1986.

Des87 Desmedt: *Society and Group Oriented Cryptography: A New Concept.* CRYPTO 1987.

DF89 Desmedt, Frankel: *Threshold Cryptosystems.* CRYPTO 1989.



one secret and single-party algorithms (Generate, Decrypt, Sign)



shared secret and distributed algorithms with threshold $t < n$

Distributed Key Generation (DKG)

GJKR07 Gennaro, Jarecki, Krawczyk, Rabin: *Secure Distributed Key Generation for Discrete-Log Based Cryptosystems.* JoC 20(1) 2007.

Preliminaries: set of n parties $P_1, \ldots, P_n$ with *partially synchronous* communication (e.g. synchronized clocks)

Assumptions:

- computing discrete logarithms modulo large primes is hard
- let p, q large primes such that $q \mid p-1$; then G_q denotes the subgroup of elements from $\mathbb{Z}_p^*$ of order q and let g, h generators of G_q such that $\log_g h$ is not known to anybody

Adversary:

- is *malicious*; can corrupt up to t parties, where $t < n/2$ (optimal threshold or t-*resilience* for a synchronous model)
- is *static*, i.e., chooses corrupted parties at the beginning
- is *rushing*, i.e., speaks last in each round of communication

Properties of Distributed Key Generation (DKG)

GJKR07 Gennaro, Jarecki, Krawczyk, Rabin: *Secure Distributed Key Generation for Discrete-Log Based Cryptosystems.* JoC 20(1) 2007.

Security: A DKG protocol is called t-*secure*, if in presence of an attacker $\mathcal{A}$ that corrupts at most t parties the following requirements for correctness and secrecy are satisfied:

(C1) all subsets of $t+1$ shares provided by honest parties (i.e. not corrupted by $\mathcal{A}$) define the same unique secret key $x \in G_q$,

(C2) all honest parties have the same public key $y = g^x \bmod p$, where x is the unique secret key guaranteed by (C1),

(C3) x is uniformly distributed in G_q,

(S1) no information on x can be learned by the adversary $\mathcal{A}$, except for what is implied by the public key $y = g^x \bmod p$

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Robustness: construction of y and reconstruction of x is possible in presence of $\leqslant t$ malicious parties that try to foil computation

Protocol New-DKG [GJKR07]

Generating common secret $x = \sum_{i \in QUAL} z_i \bmod q$:

1. Each party P_i performs Pedersen-VSS of secret z_i as a dealer
   - **(a)** Choose random polynomials $f_i(z) = a_{i0} + a_{i1}z + \cdots + a_{it}z^t$ and $f'_i(z) = b_{i0} + b_{i1}z + \cdots + b_{it}z^t$ over $\mathbb{Z}_q$, let $z_i = a_{i0} = f_i(0)$, broadcast commitment $C_{ik} = g^{a_{ik}} h^{b_{ik}} \bmod p$ for $k = 0, \ldots, t$, and send shares $s_{ij} = f_i(j) \bmod q$ and $s'_{ij} = f'_i(j) \bmod q$ to party P_j
   - **(b)** Each party P_j verifies that $g^{s_{ij}} h^{s'_{ij}} = \prod_{k=0}^{t} (C_{ik})^{j^k} \bmod p$
   - **(c), (d)** Resolution of received complaints from verification of the shares
2. Each party builds the set QUAL (non-disqualified parties)
3. Each party P_i computes secret share as $x_i = \sum_{j \in QUAL} s_{ji} \bmod q$

Extracting $y = g^x \bmod p$: (only non-disqualified parties, i.e., $i \in QUAL$)

4. Each party P_i exposes $y_i = g^{z_i} \bmod p$ via Feldman-VSS:
   - **(a)** Each party P_i broadcasts $A_{ik} = g^{a_{ik}} \bmod p$ for $k = 0, \ldots, t$
   - **(b)** Each party P_j verifies that $g^{s_{ij}} = \prod_{k=0}^{t} (A_{ik})^{j^k} \bmod p$
   - **(c)** Run reconstruction to compute z_ℓ, $f_\ell(z)$, $A_{\ell k}$, if P_ℓ corrupted

   Set $y_i = A_{i0} = g^{z_i} \bmod p$ and compute $y = \prod_{i \in QUAL} y_i \bmod p$

Threshold Decryption (ElGamal Cryptosystem)

CGS97 Cramer, Gennaro, Schoenmakers: *A Secure and Optimally Efficient Multi-Authority Election Scheme.* EUROCRYPT 1997.

Encryption: message $m \in G_q$ is encrypted as $(g^k, y^k m)$, where $y \in G_q$ is the corresponding public key and $k \overset{R}{\in} \mathbb{Z}_q$ a fresh secret

Decryption:

1. Each P_i broadcasts its decryption share $r_i = (g^k)^{x_i} \bmod p$ together with a *zero-knowledge proof of knowledge* that shows $\log_g v_i = \log_{(g^k)} r_i$, where $v_i = g^{x_i} \bmod p$ is a public verification key that can be computed after New-DKG 4.(c):

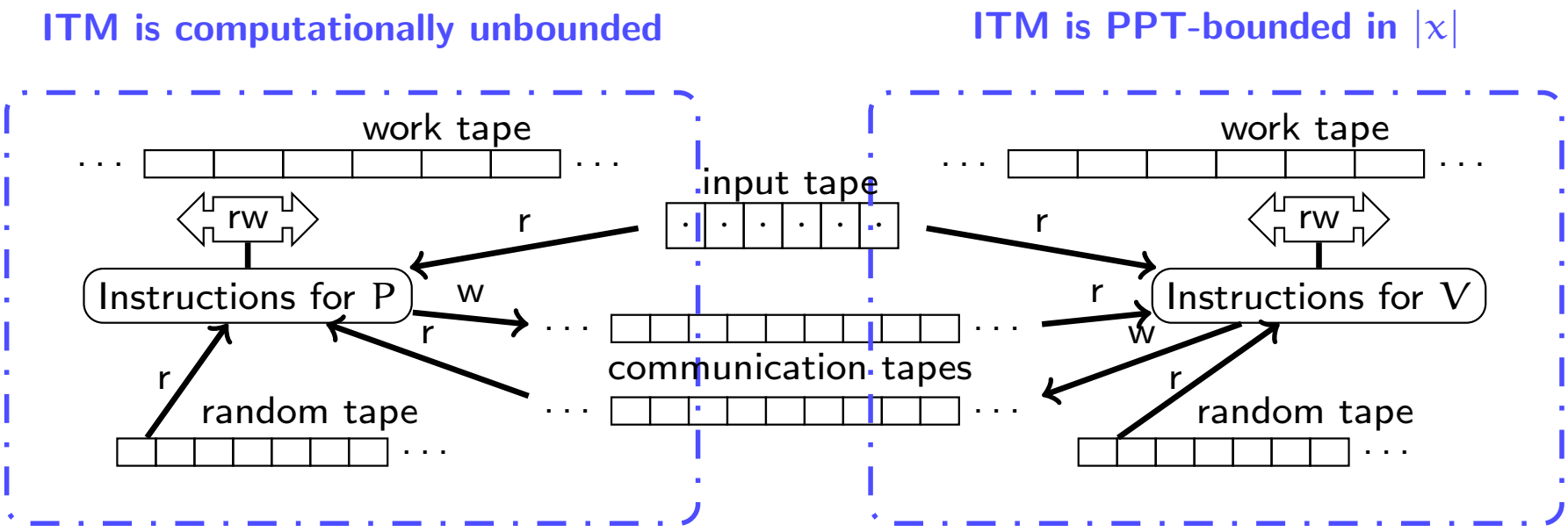
$$v_i = \prod_{j \in \mathsf{QUAL}} \prod_{k=0}^{t} (A_{jk})^{i^k} \bmod p$$

2. Combine $t+1$ correct decryption shares by using Lagrange interpolation in exponent: $m = (y^k m) / \prod_{j \in \Lambda} r_j^{\lambda_{j,\Lambda}} \bmod p$

Interactive Proof Systems

GMR85 Goldwasser, Micali, Rackoff: *The Knowledge Complexity of Interactive Proof Systems.* STOC 1985. (SIAM J. Comput. 18(1) 1989)

Probabilistic *Interactive Proof System* (IP) for a statement $x \in L$

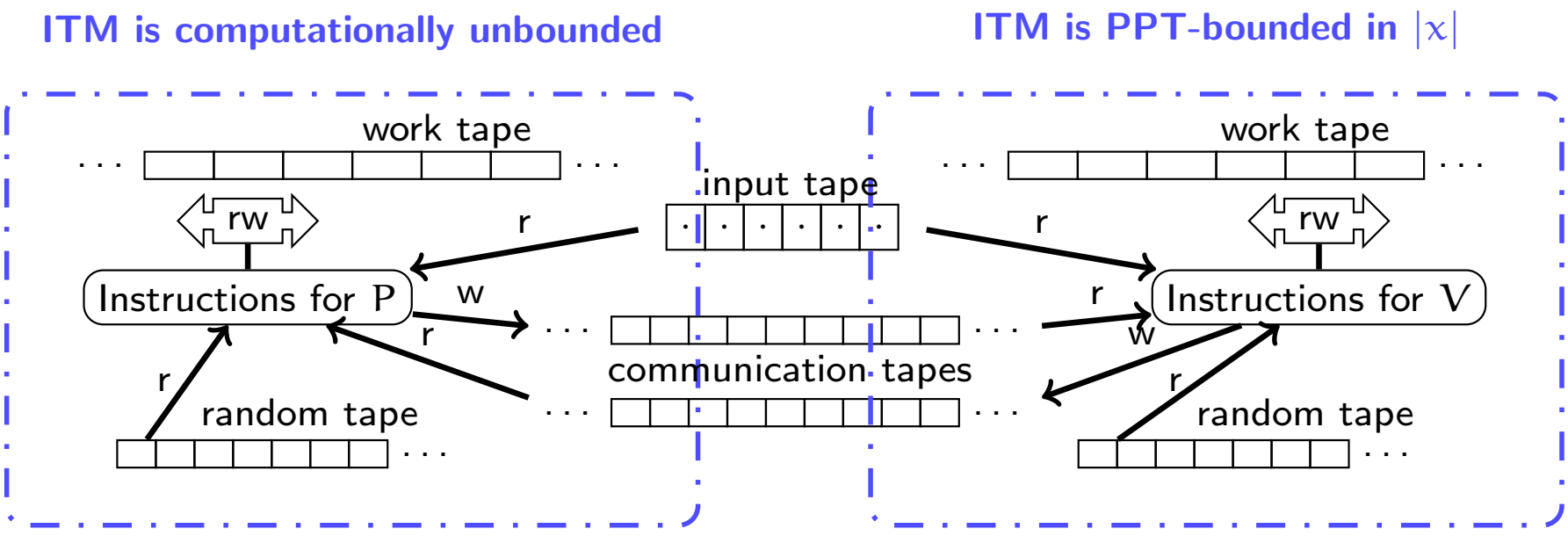


Completeness: if the statement is true, the honest verifier V will be convinced of this fact by an honest prover P

Soundness: if the statement is false, no cheating prover P can convince the honest verifier V that it is true, except with some small probability (soundness error)

Zero-Knowledge Proof

Probabilistic *Interactive Proof System* (IP) for a statement $x \in L$



Zero-Knowledge: if the statement is true, no cheating verifier V learns anything other than the fact that $x \in L$

Theorem (Goldreich, Micali, Wigderson 1986; Ben-Or et al. 1988)

$\mathcal{NP} \subseteq \mathcal{IP}_{\mathrm{CZK}}$, if one-way functions exist; $\mathcal{IP} = \mathcal{IP}_{\mathrm{CZK}}$, if one-way functions exist.

Theorem (Shamir 1990)

$\mathcal{IP} = \mathcal{PSPACE}$.

Example: ZK Proof of Graph Isomorphism $\in \mathcal{IP}_{\mathsf{PZK}}$

input: graphs G_1, G_2, **statement:** $G_1 \cong G_2$, **secret:** π s.t. $G_1 = \pi(G_2)$

P: $\sigma \overset{R}{\in} \{1,2\}$, $\psi \overset{R}{\in} \Pi(G_\sigma)$, compute $H = \psi(G_\sigma)$, send H to V

V: (challenge) $\tau \overset{R}{\in} \{1,2\}$, send τ to P

P: compute $\rho = \left\{ \begin{array}{ll} \psi & \text{if } \tau = \sigma \\ \psi \circ \pi & \text{if } \tau \neq \sigma \text{ and } \sigma = 1 \\ \psi \circ \pi^{-1} & \text{if } \tau \neq \sigma \text{ and } \sigma = 2 \end{array} \right]$, send ρ to V

V: check whether $H = \rho(G_\tau)$ holds and accept resp. reject

Completeness: honest prover P can always construct ρ s.t. $H = \rho(G_\tau)$

Soundness: error prob. $1/2$ (can be reduced by sequential repetitions)

Zero-Knowledge: $\forall \mathcal{V} : \exists \mathcal{S}$ (simulator, expected PPT) with identically distributed output as the view of the above protocol

(simulator $\mathcal{S}$ picks $\sigma' \overset{R}{\in} \{1,2\}, \psi' \overset{R}{\in} \Pi(G_{\sigma'})$, computes $H' = \psi'(G_{\sigma'})$ and outputs transcript (H', τ', ψ'), if $\mathcal{V}$'s challenge $\tau = \sigma'$, otherwise restart)

Zero-Knowledge Proof of Knowledge

GMR85 Goldwasser, Micali, Rackoff: *The Knowledge Complexity of Interactive Proof Systems.* STOC 1985.

FFS87 Feige, Fiat, Shamir: *Zero-Knowledge Proofs of Identity.* STOC 1987.

BG92 Bellare, Goldreich: *On Defining Proofs of Knowledge.* CRYPTO 1992.

$\mathrm{L} \in \mathcal{NP}$: show that P "knows" a corresponding short *witness* ω for proving membership of each $x \in \mathrm{L}$ without revealing these secrets

Definition (informal)

The protocol Π is a *Zero-Knowledge Proof of Knowledge* (ZKPoK), iff

1. Π is an Interactive Proof System with zero-knowledge property,
2. for any ITM $\mathcal{P}$ that make V accept the input x there exists a PPT-bounded *knowledge extractor* $\mathcal{M}$ that can rewind the execution of $\mathcal{P}$ (i.e. reset the head and content of work tape, the heads of input and random tape and the state of its finite control unit) and thus extract a witness ω showing membership $x \in \mathrm{L}$.

Σ-protocol: three-round ZKPoK (P: commitment, V: challenge, P: response)

Example: Equality of Discrete Logarithms (Σ-protocol)

CP92 Chaum, Pedersen: *Wallet Databases with Observers.* CRYPTO 1992.

Threshold Decryption [CGS97] (ElGamal Cryptosystem)

Let p and q be large primes such that $q \mid p-1$; then G_q denotes the unique subgroup of elements from $\mathbb{Z}_p^*$ of order q and g denotes a generator of G_q.

public verification key of P_i: $v_i = g^{x_i} \bmod p$

decryption share of P_i: $r_i = (g^k)^{x_i} \bmod p$

input: p, q, g, v_i, g^k, r_i, **statement:** $\log_g v_i = \log_{(g^k)} r_i \pmod p$

P: $s \overset{R}{\in} \mathbb{Z}_q$, commit to $(a, b) = (g^s, (g^k)^s)$, send (a, b) to V

V: (challenge) $c \overset{R}{\in} \mathbb{Z}_q$ and send c to P

P: compute $d = cx_i + s \bmod q$ and send d to V

V: accept, if $g^d = a(v_i)^c \pmod p$ and $(g^k)^d = b(r_i)^c \pmod p$

Knowledge Extractor: rewind $\mathcal{P}$ to get (c_1, d_1) and (c_2, d_2) for same s; since $c_1 \neq c_2$ it can compute $x_i = \frac{d_1 - d_2}{c_1 - c_2} = \frac{(c_1 x_i + s) - (c_2 x_i + s)}{c_1 - c_2} \bmod q$

Security of ElGamal in $\mathbb{Z}_p^*$ (e.g. in OpenPGP)

Sakurai, Shizuya: *Relationships among the Computational Powers of Breaking Discrete Log Cryptosystems.* EUROCRYPT 1995.

Sakurai, Shizuya: *A Structural Comparison of the Computational Difficulty of Breaking Discrete Log Cryptosystems.* JoC 11(1), 1998.

- Computing $m \in \mathbb{Z}_p^*$ from given $g, y, g^k, y^k m \in \mathbb{Z}_p^*$ is hard, iff the Computational Diffie-Hellman (CDH) problem is hard

$\rightsquigarrow$ ElGamal in $\mathbb{Z}_p^*$ is OW-CPA secure under CDH assumption

Tsiounis, Yung: *On the Security of ElGamal based Encryption.* PKC 1998.

- Distinguishing $m, \bar{m} \in G_q$ given $g, y, g^k, y^k m, g^{\bar{k}}, y^{\bar{k}} \bar{m} \in G_q$ is hard, iff the Decision Diffie-Hellman (DDH) problem is hard

$\rightsquigarrow$ ElGamal in G_q is IND-CPA secure under DDH assumption

Threshold Signature Scheme (DSA/DSS Variant)

CGJKR99 Canetti, Gennaro, Jarecki, Krawczyk, Rabin: *Adaptive Security for Threshold Cryptosystems.* CRYPTO 1999.

Preliminaries: set of n parties $P_1, \ldots, P_n$ with *partially synchronous* communication (e.g. synchronized clocks)

Assumptions:

- computing discrete logarithms modulo large primes is hard
- let p, q large primes such that $q \mid p - 1$; then G_q denotes the subgroup of elements from $\mathbb{Z}_p^*$ of order q and let g, h generators of G_q such that $\log_g h$ is not known to anybody

Adversary:

- can corrupt up to $\hat{t}$ parties, where $\hat{t} < n/2$ (optimal threshold or $\hat{t}$-*resilience* for a synchronous model)
- is *adaptive*, i.e., can choose corrupted parties during attack
- is *rushing*, i.e., speaks last in each round of communication

Protocol DL-Key-Gen (optimally-resilient) [CGJKR99]

Generating common secret $\widehat{x} = \sum_{i \in \widehat{QUAL}} \widehat{z}_i \bmod q$:

1. Parties execute Joint-RVSS (i.e. each P_i performs a Pedersen-VSS of random secret $\widehat{z}_i$ as a dealer) and get $\widehat{C}_{ik}$, $\widehat{QUAL}$, shares $\widehat{x}_i$, $\widehat{x}'_i$

Extracting $\widehat{y} = g^{\widehat{x}} \bmod p$: (only non-disqualified parties, i.e., $i \in \widehat{QUAL}$)

2. Each party P_i broadcasts $\widehat{A}_i = g^{\widehat{z}_i} \bmod p$ and $\widehat{B}_i = h^{\widehat{f}'_i(0)} \bmod p$ such that $\widehat{C}_{i0} = \widehat{A}_i \cdot \widehat{B}_i \pmod p$ holds

3.–6. Each party P_i proves with a *distributed zero-knowledge proof of knowledge* that the above split of the commitment $\widehat{C}_{i0}$ is correct

7. Run reconstruction to compute $\widehat{z}_j$ and $\widehat{A}_j$, if some P_j are corrupted

8. The public value $\widehat{y}$ is set to $\widehat{y} = \prod_{i \in \widehat{QUAL}} \widehat{A}_i \bmod p$

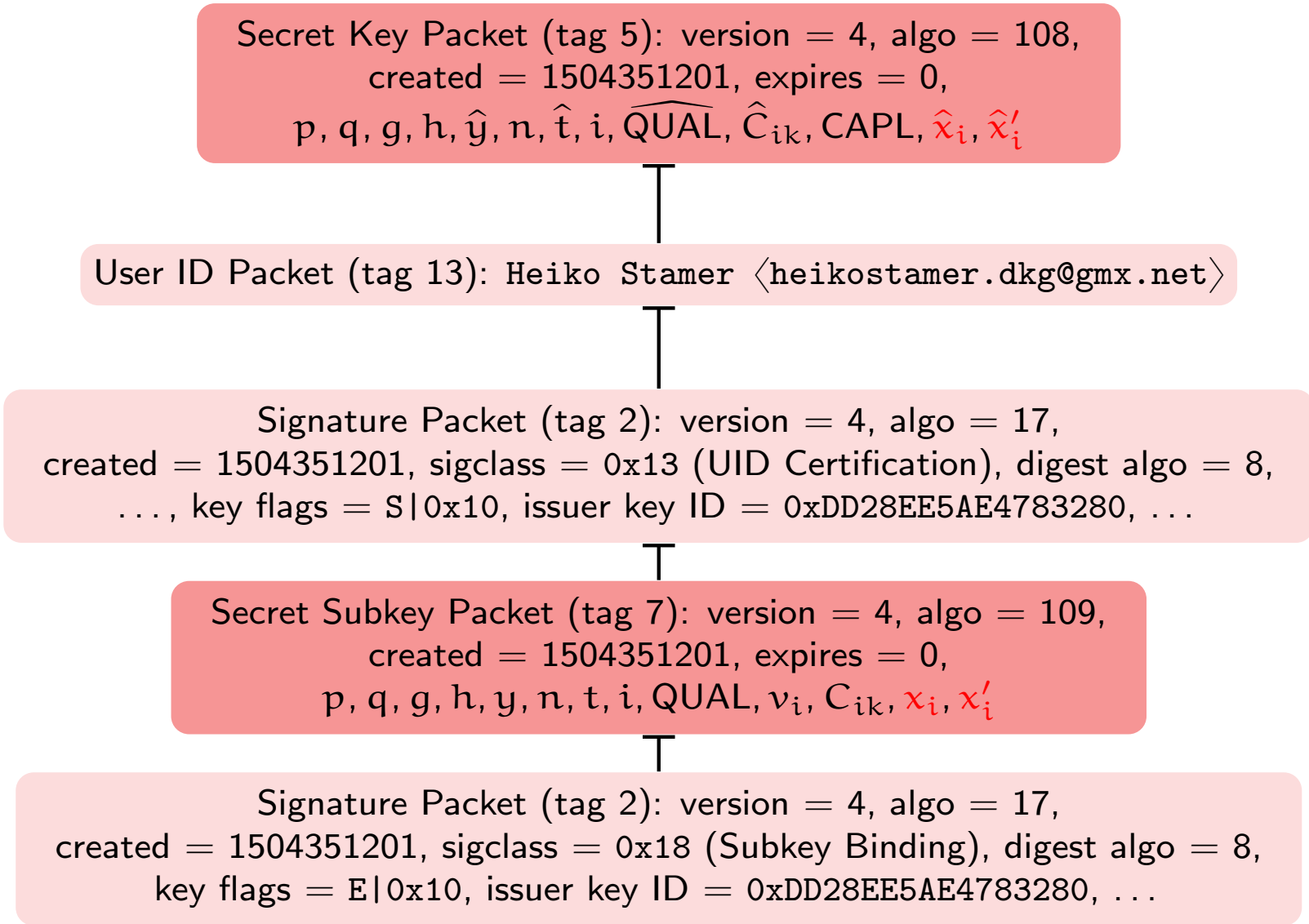
9. P_i erases all secrets generated in this protocol aside from $\widehat{x}_i$ and $\widehat{x}'_i$

Protocol DSS-Sig-Gen ($\geqslant 2\hat{t}+1$, not optimal) [CGJKR99]

1. Generate $r = g^{k^{-1}} \bmod p \bmod q$:
   - **(a)** Parties execute Joint-RVSS to generate k and get shares k_i, k'_i
   - **(b)** Parties execute DL-Key-Gen to generate a and get g^a and a_i, a'_i
   - **(c)** Back-up k_i and a_i using Pedersen-VSS; P_i is required to prove correctness with a *distributed zero-knowledge proof of knowledge* (at least $\hat{t}+1$ sound proofs and corrupted parties will be ignored)
   - **(d)** Each P_i shares $\hat{v}_i = a_i k_i \bmod q$ using Pedersen-VSS and proves correctness with a *distributed zero-knowledge proof of knowledge*
   - **(e)** Run reconstruction of a_j and k_j, if some P_j are corrupted, and set $\hat{v}_j = a_j k_j$; bad values are sieved out using commitments from (c)
   - **(f)** Each P_i broadcasts its shares of the $\hat{t}$-degree polynomial, which is a linear combination of the shares $\hat{v}_1, \ldots, \hat{v}_{2\hat{t}+1}$ received in step (d)
   - **(g)** Each P_i computes locally μ^{-1} and $r = (g^a)^{\mu^{-1}} \bmod p \bmod q$
2. Generate $s = k(m + \hat{x}r) \bmod q$:
   - Parties perform steps equivalent to 1.(c)–(f), with the values $m + \hat{x}_i r$ taking the role of a_i's, and with s taking the role of μ (in step 1.(c) only the back-up of $m + \hat{x}_i r$ is required; reuse k_i's)
3. Party P_i erases all secrets generated in this protocol

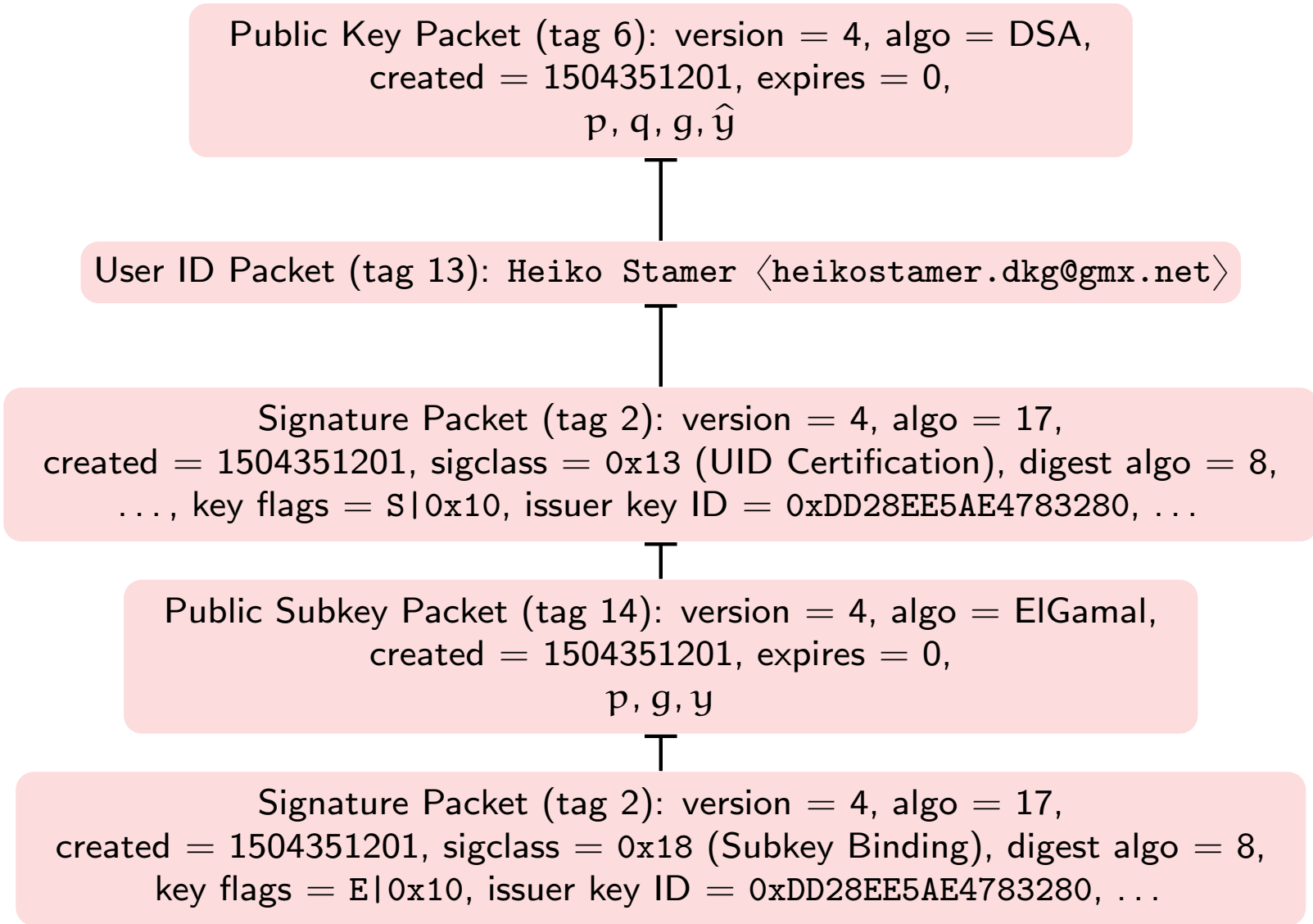
Implementation for OpenPGP [RFC4880]

Case 1: Each party P_i has a shared primary DSA key (for signing) and a shared ElGamal subkey (for encryption)



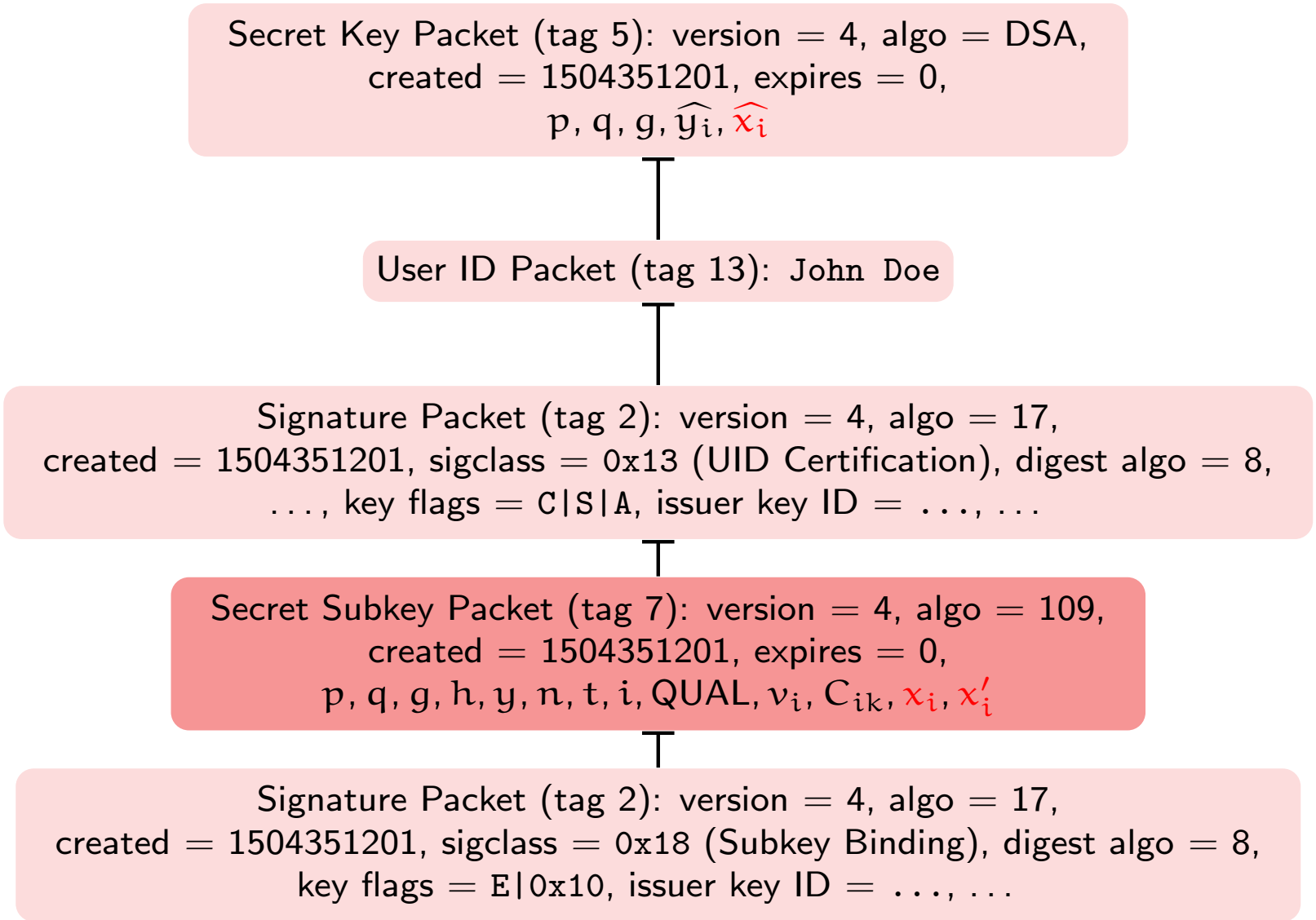
Corresponding OpenPGP-compatible Public Key

Case 1: Each party P_i has shared primary DSA key (for signing) and a shared ElGamal subkey (for encryption)



Other Cases

Case 2: Each party P_i has an individual primary DSA key (for signing etc.) and a shared ElGamal subkey (for encryption)



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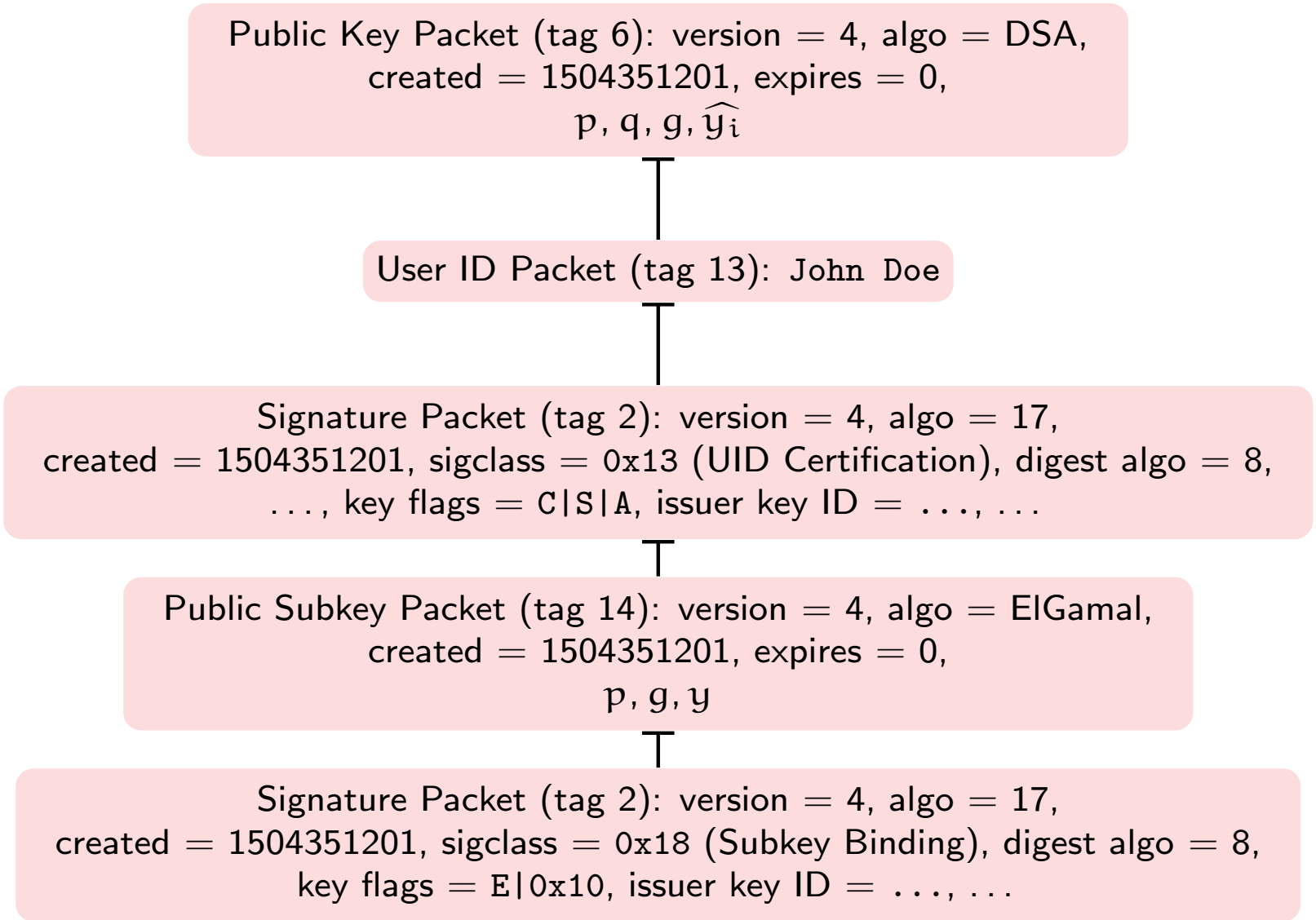


Other Cases

Case 3: Each party P_i has only a shared primary DSA key

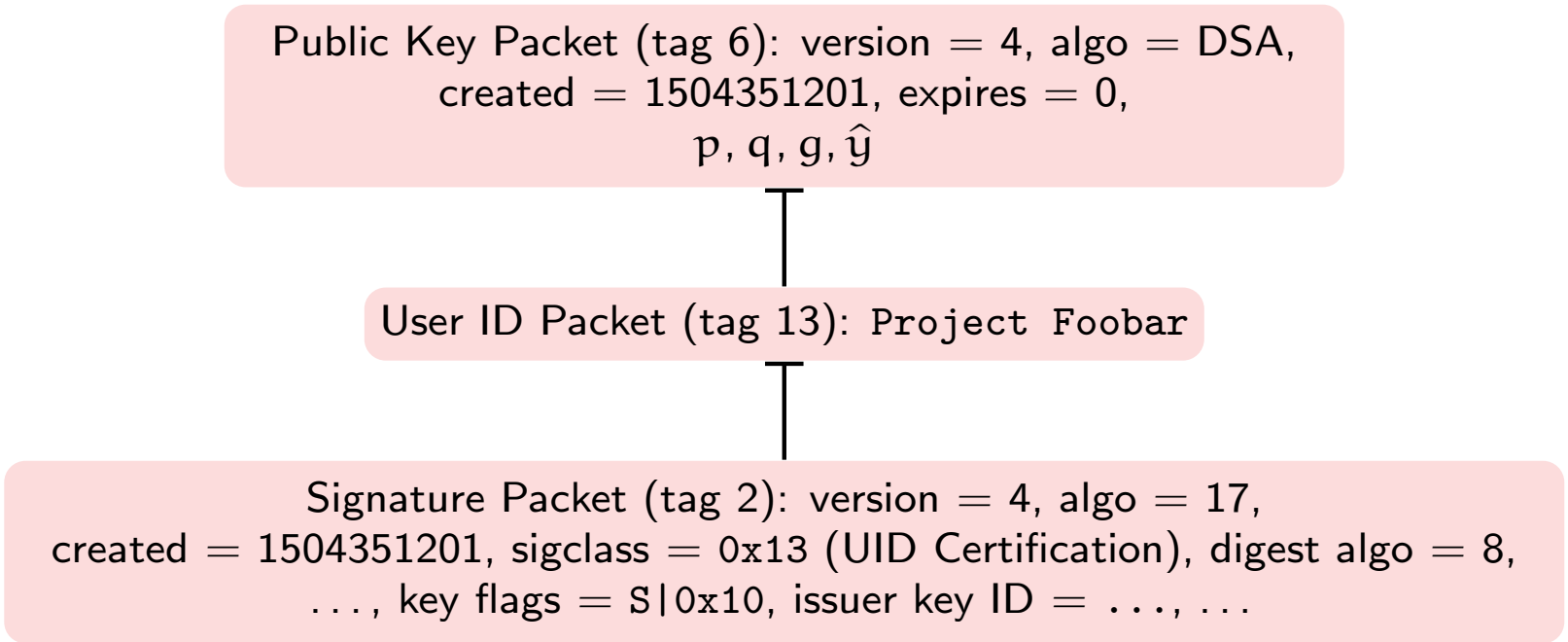
Secret Key Packet (tag 5): version $=$ 4, algo $=$ 108,
created $=$ 1504351201, expires $=$ 0,
$p, q, g, h, \widehat{y}, n, \widehat{t}, i, \widehat{QUAL}, \widehat{C}_{ik}$, CAPL, $\widehat{x}_i, \widehat{x}'_i$

User ID Packet (tag 13): `Project Foobar`

Signature Packet (tag 2): version $=$ 4, algo $=$ 17,
created $=$ 1504351201, sigclass $=$ `0x13` (UID Certification), digest algo $=$ 8,
$\ldots$, key flags $=$ `S|0x10`, issuer key ID $=$ $\ldots$, $\ldots$

Corresponding OpenPGP-compatible Public Key

Case 3: Each party P_i has only a shared primary DSA key



Implementation in LibTMCG resp. DKGPG

WARNING: Code is in EXPERIMENTAL state and should not be used for production!

New-DKG, New-TSch:

`GennaroJareckiKrawczykRabinDKG.cc`

contains $\approx$ 1.750 LOC

Joint-RVSS, Joint-ZVSS, DL-Key-Gen, DSS-Sig-Gen:

`CanettiGennaroJareckiKrawczykRabinASTC.cc`

contains $\approx$ 4.500 LOC (+900 LOC `PedersenVSS.cc`)

Reliable Broadcast: `CachinKursawePetzoldShoupSEABP.cc`

contains $\approx$ 850 LOC; RBC Protocol [CKPS01] for $t < n/3$

OpenPGP: `CallasDonnerhackeFinneyShawThayerRFC4880.cc`

contains $\approx$ 3.650 LOC

3rd Party Libraries:

- GNU Multiple Precision Arithmetic Library (`libgmp`) $\geqslant$ 4.2.0
- GNU Crypto Library (`libgcrypt`) $\geqslant$ 1.6.0 (random, crypto primitives)

P2P Message Exchange: GNUnet $\geqslant$ 0.10.2 (not yet released!), TCP/IP interface (e.g. TOR hidden service with port forwarding and `torsocks`)

User Interface (DKGPG = Distributed Privacy Guard)

dkg-gencrs domain parameter generation (p, q, g) of G_q

- **-f SEED** generate domain parameters according to FIPS 186-4

dkg-generate distributed key generation (DSA+ElGamal)

- **-e TIME** expiration time of generated keys in seconds
- **-g STRING** domain parameters of G_q (common reference string)
- **-H STRING** hostname of this peer for TCP/IP (e.g. onion address)
- **-P STRING** password list to encrypt/authenticate TCP/IP connections
- **-s INTEGER** threshold $\hat{t}$ for DL-Key-Gen protocol (signature scheme)
- **-t INTEGER** threshold t for New-DKG protocol (encryption scheme)

dkg-decrypt threshold decryption (ElGamal)

- **-i FILENAME** input file with ASCII-armored encrypted message
- **-n** switch to non-interactive mode (using NIZK proofs; ROM)
- **-o FILENAME** output file with decrypted message

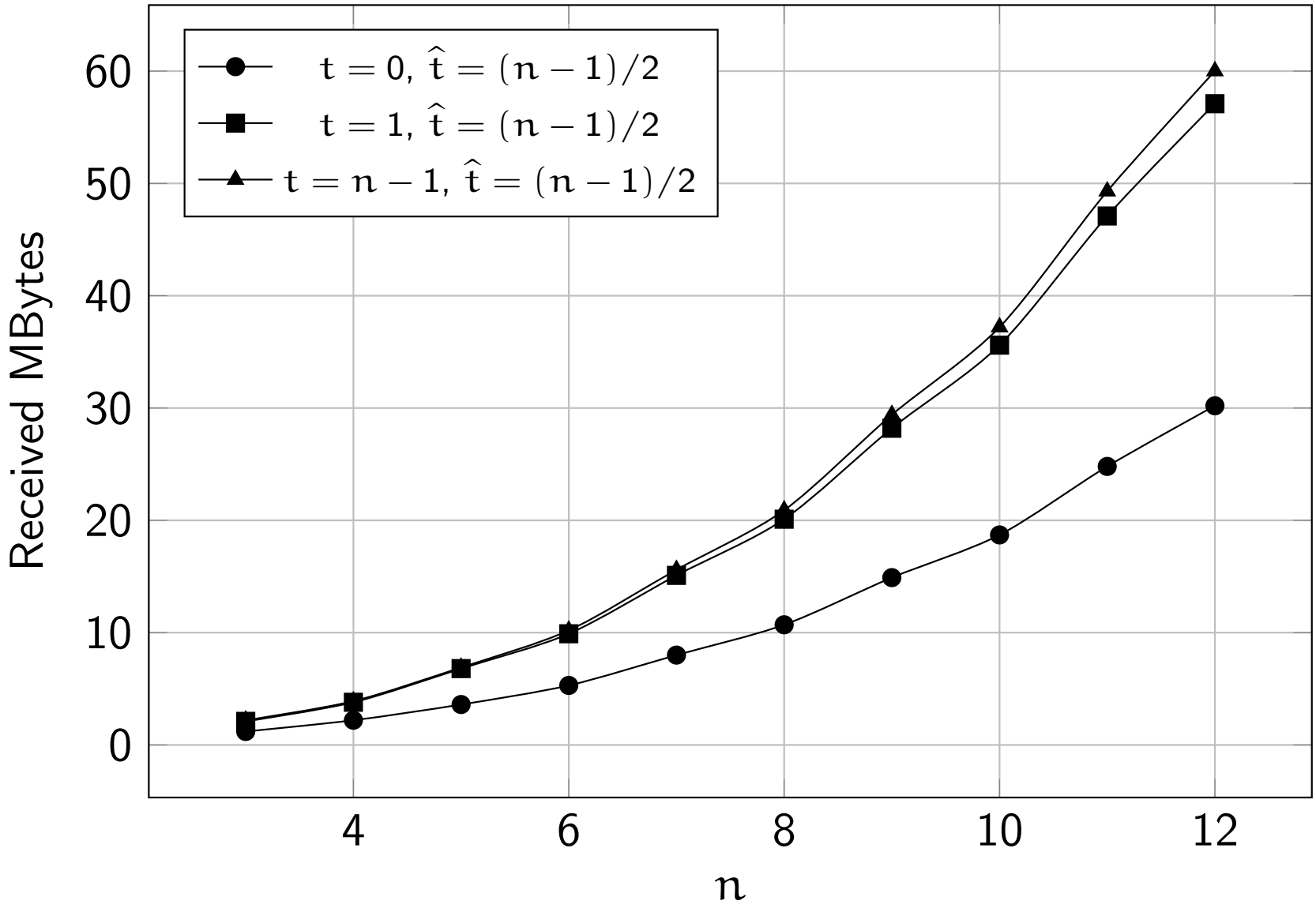
dkg-sign threshold signature generation (DSA)

- **-e TIME** expiration time of generated signature in seconds
- **-i FILENAME** create detached signature from given input file
- **-o FILENAME** output file with detached signature

dkg-revoke threshold key revocation (DSA+ElGamal)

- **-r INTEGER** reason for revocation (OpenPGP machine-readable code)

Network Traffic (`dkg-generate` with $|p| = 2048$, $|q| = 256$)



Usage Scenarios

Mailbox for informants/whistleblowers: *distributed power*

- Imagine a newspaper or broadcast media with n responsible journalists in the editorial department/board
- There are authenticated private channels (e.g. already exchanged GNUnet/OpenPGP keys) between the journalists
- At least $t + 1$ of these journalists should be necessary to decrypt messages received in this dedicated mailbox

Shared mailbox for groups of political activists:

- Similar scenario as above with additional signing capability

Protection of encryption/signing keys of a single person:

- Imagine n devices with different security levels (e.g. OS)
- At least $t + 1$ resp. $2\widehat{t} + 1$ of these devices (storing the key shares) must work together to decrypt resp. sign messages

Remaining Work (TODO)

Cryptographic Protocols/Schemes:

- $\mathfrak{h}$-generation protocol with *distributed zero-knowledge PoKs*
- Proactive refresh of shares protects against mobile adversary

Software Engineering:

- Package (`dkgpg`) containing only the DKG tools
- Fully asynchronous communication model without artifical timing assumptions, cf. related work [KG09, KHG12]
- State-based representation of the protocols
- Generic group abstraction layer in LibTMCG (e.g. for ECC)

How can you help?

- Compiling and testing the software on different platforms
- Review design criterias and invent new usage scenarios
- Review source code and report vulnerabilities/bugs
- Help with implementation of missing protocols (e.g. RSA, ECC)
- Packaging for different distributions of free/libre software
- Write standardization draft and advocate for including threshold cryptography in revised RFC 4880bis or other

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