Distributed Key Generation and Threshold Decryption for OpenPGP

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26. Krypto-Tag, June 2017, SUSE, Nürnberg

Background

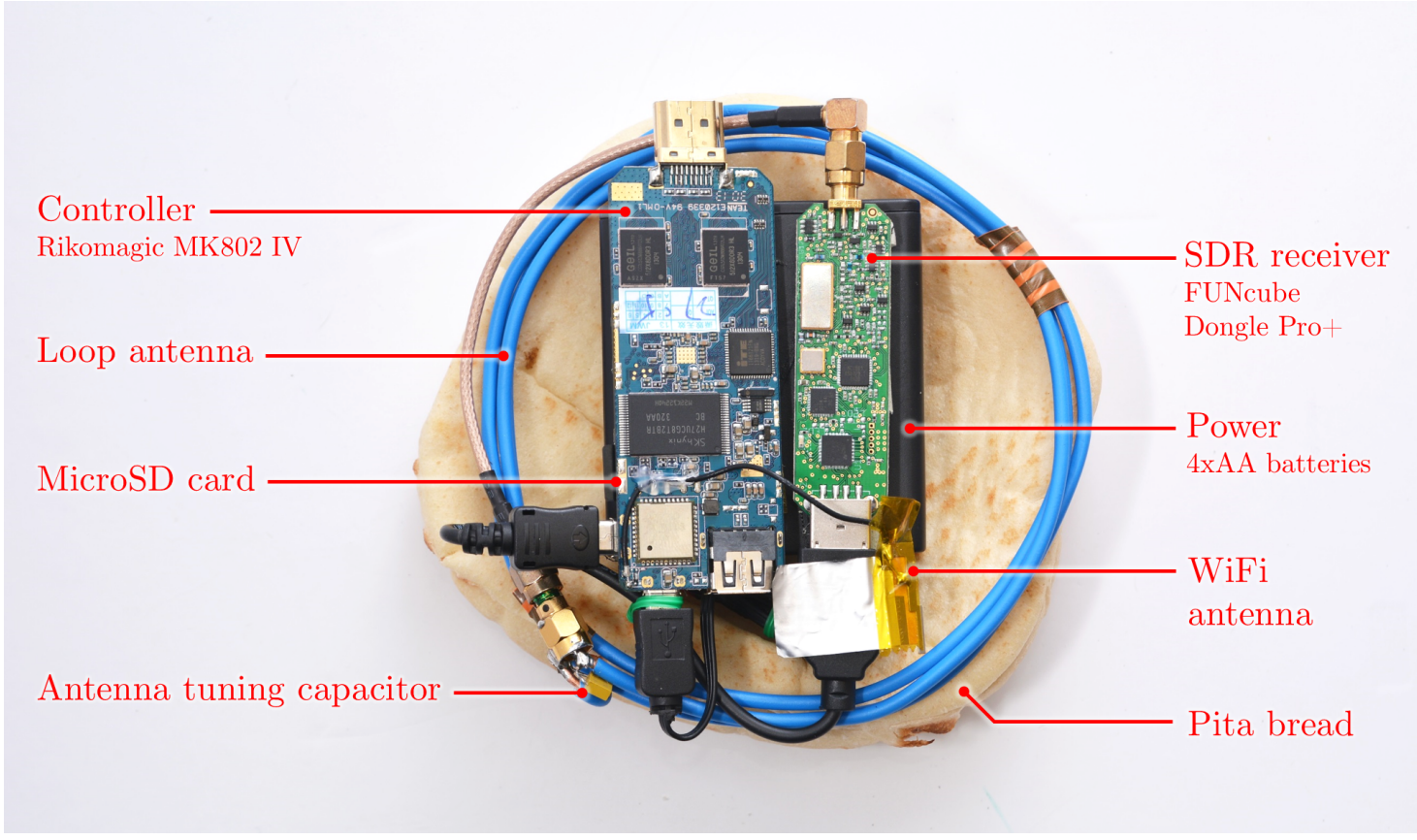
Source: Bruno Sanchez-Andrade Nuño, CC BY 2.0

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?



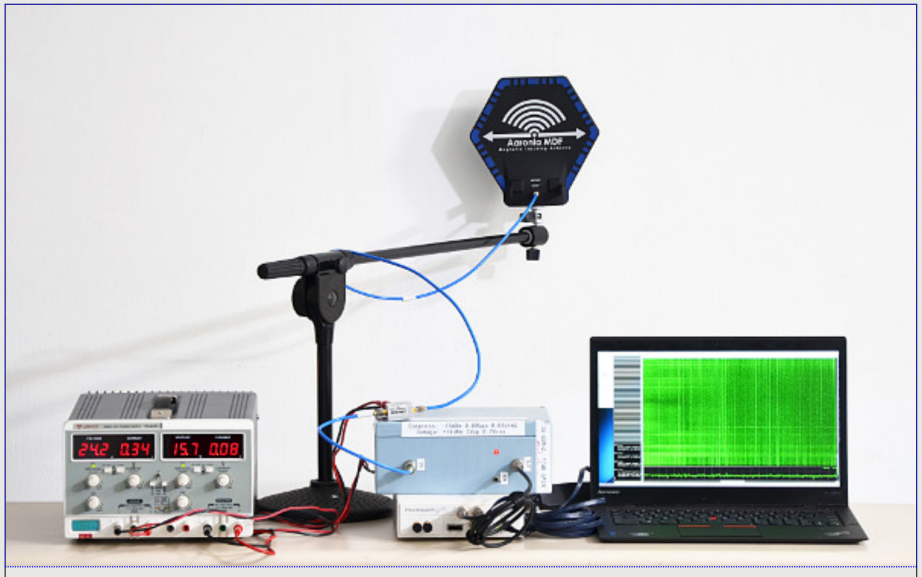
Daniel Genkin, Lev Pachmanov, Itamar Pipman, and Eran Tromer.
Stealing Keys from PCs using a Radio: Cheap Electromagnetic Attacks on Windowed Exponentiation. http://eprint.iacr.org/2015/170

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)

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 and q big primes such that $q \mid p-1$; then G_q denotes the subgroup of elements from $\mathbb{Z}_p^*$ of order q and g, h are generators of G_q such that $\log_g h$ is not known to adversary

Adversary:

- 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

Distributed Key Generation (DKG)

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Security: A DKG protocol is called t-*secure*, if in presence of an attacker 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 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 guaranteed by (C1),

(C3) x is uniformly distributed in G_q,

(S1) no information on x can be learned by the adversary except for what is implied by $y = g^x \bmod p$ ($\exists \mathcal{S}$: PPT simulator).

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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

Efficient Distributed Key Generation

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 that corrupts at most t parties the following requirements for correctness and secrecy are satisfied:

(C1') there is an efficient procedure that on input the n shares submitted by the parties and the public information produced by the DKG protocol, outputs the unique value $x \in G_q$, even if up to t shares are submitted by faulty parties,

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

(C3) x is uniformly distributed in G_q,

(S1) no information on x can be learned by the adversary except for what is implied by $y = g^x \bmod p$ ($\exists \mathcal{S}$: PPT simulator).

Protocol New-DKG [GJKR07]

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

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 $z_i, f_i(z), A_{ik}$, if P_i 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 public key and secret $k \in \mathbb{Z}_q$ is chosen randomly

Decryption:

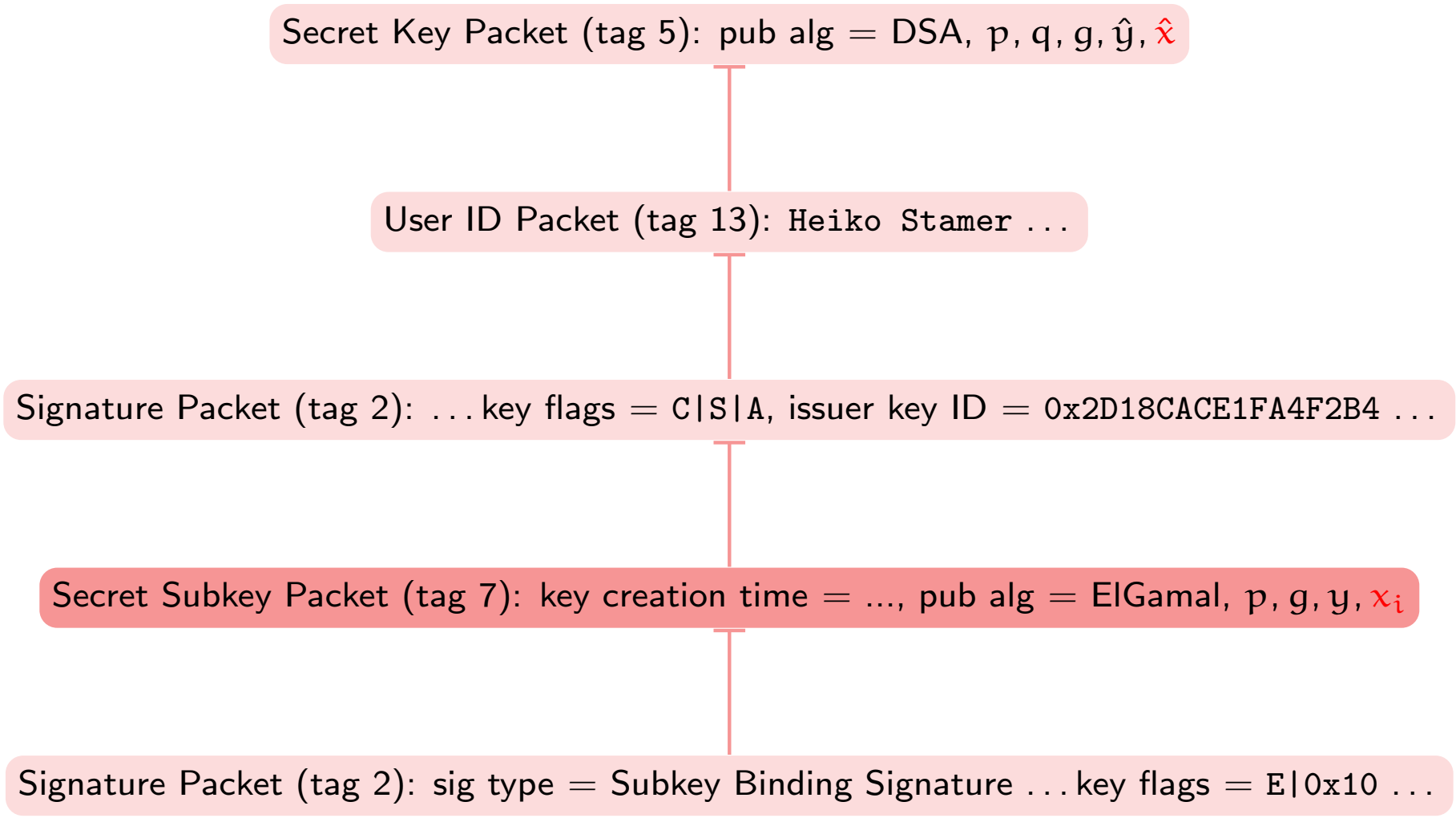
1. Each party P_i broadcast decryption share $r_i = (g^k)^{x_i} \bmod p$ together with a *zero-knowledge proof of knowledge* that $\log_g v_i = \log_{(g^k)} r_i$ holds, where $v_i = g^{x_i} \bmod p$ is a public verification key that can be computed after New-DKG 4.(a):

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

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

Implementation for OpenPGP [RFC4880]

Current State: Each party P_i has its individual primary DSA key (for signing etc.) and a common ElGamal subkey (for encryption)



But where to store index i and verification key v_i?

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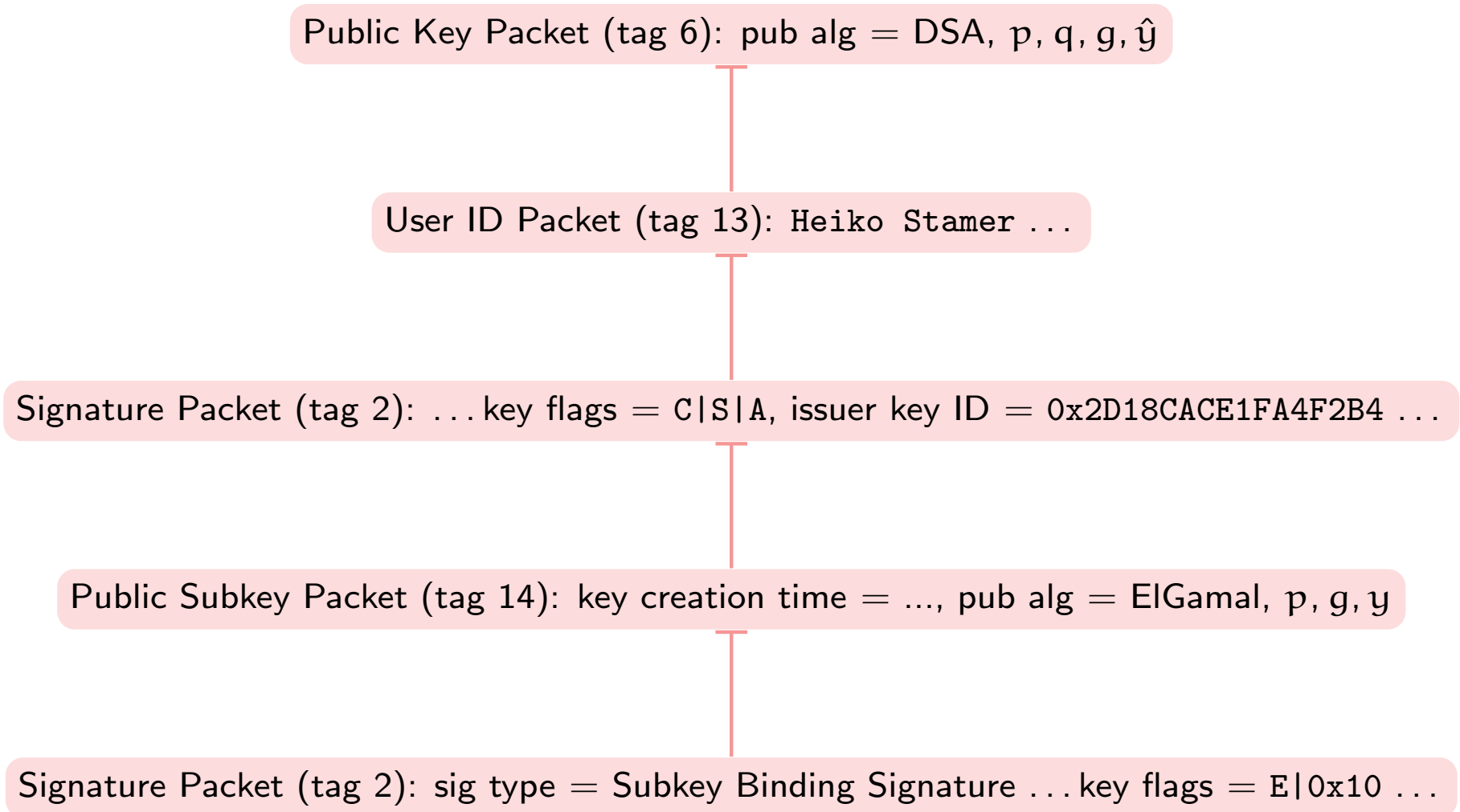

Reusing x_i is probably a bad idea. Isn't it?

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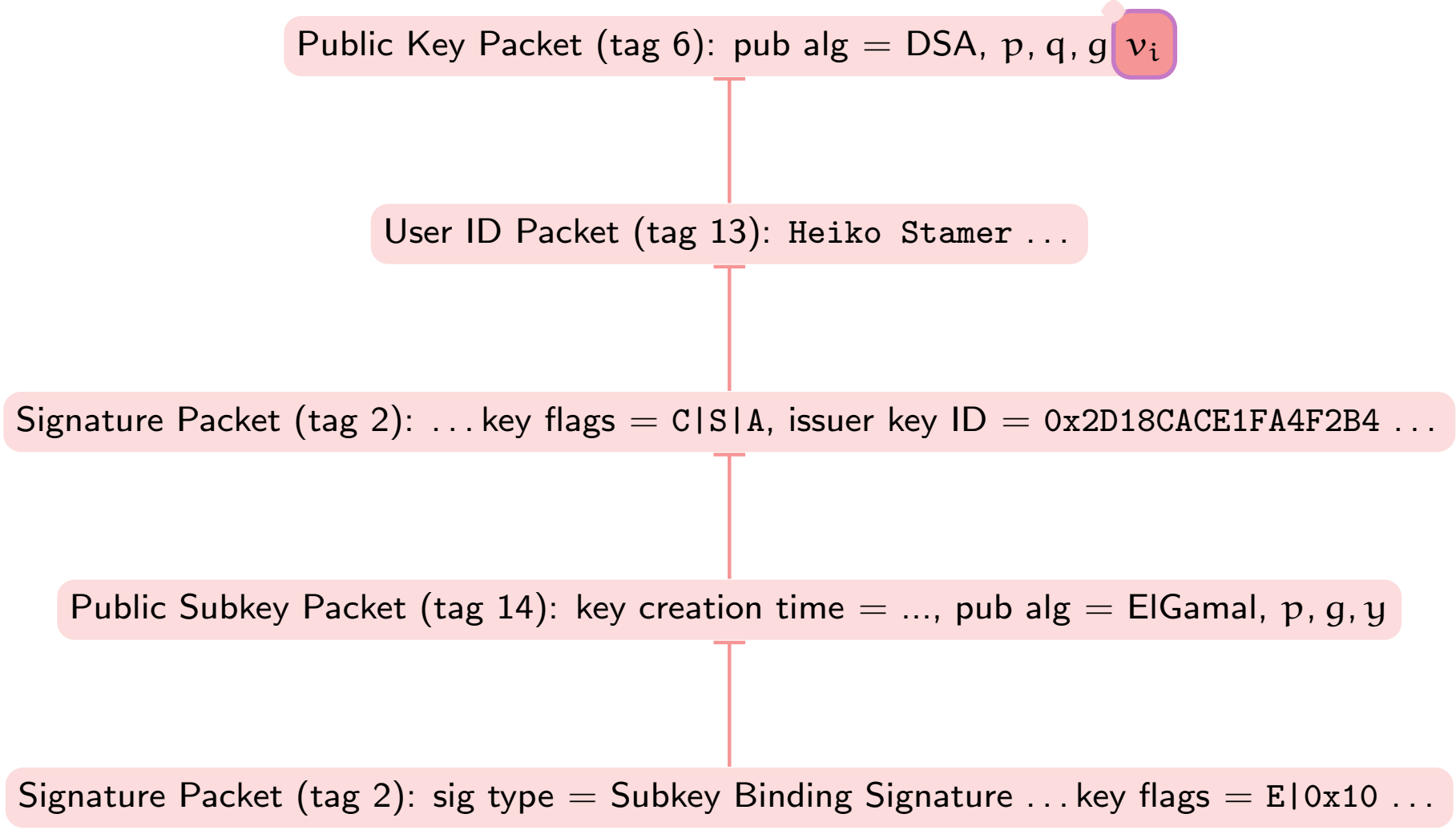

Implementation in LibTMCG

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

New-DKG: `GennaroJareckiKrawczykRabinDKG.cc`
contains $\approx$ 1.600 LOC (incl. New-TSch)

Reliable Broadcast: `CachinKursawePetzoldShoupSEABP.cc`
contains $\approx$ 700 LOC; RBC Protocol [CKPS01] for $t < n/3$

OpenPGP: `CallasDonnerhackeFinneyShawThayerRFC4880.cc`
contains $\approx$ 2.800 LOC

3rd Party Libaries:

- 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!)

`dkg-gencrs` `dkg-generate` `dkg-encrypt` `dkg-decrypt`

Usage scenarios

Mailbox for informants/whistleblowers: *freedom of press*

- Imagine a newspaper or broadcast media with n responsible journalists in the editorial department
- There are authenticated private channels (e.g. already exchanged 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

Protection of encryption keys against (gov.) malware:

- Imagine n devices with different security level (e.g. OS)
- At least $t + 1$ of these devices storing key shares should work together in order to decrypt messages

Remaining work

Cryptographic Protocols/Schemes:

- Threshold signature scheme for DSS/DSA
  - Gennaro, Jarecki, Krawczyk, Rabin: *Robust Threshold DSS Signatures*. EUROCRYPT 1996.
  - Gennaro, Goldfeder, Narayanan: *Threshold-optimal DSA/ECDSA Signatures and an Application to BitCoin Wallet Security*. ACNS 2016.
- Interactive variant of verifying decryption shares to stay in so-called *standard model* without random oracle assumption
- $\mathfrak{h}$-generation protocol with *distributed zero-knowledge PoKs*
- Adaptive security (add a zero-knowledge PoK in step 4. of New-DKG)

Software Engineering:

- Package (`dkg-openpgp`?) containing only the DKG tools
- Full compliance with OpenPGP standard
- Fully asynchronous communication model without artifical timing assumptions, cf. related work [KG09, KHG12]
- State-based representation of New-DKG
- Generic group abstraction layer in LibTMCG (e.g. for ECC)

How can you help?

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

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Network Working Group, Request for Comments, No. 4880, November 2007.

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