Verteilte Schlüsselerzeugung für OpenPGP

Distributed Privacy Guard (DKGPG)

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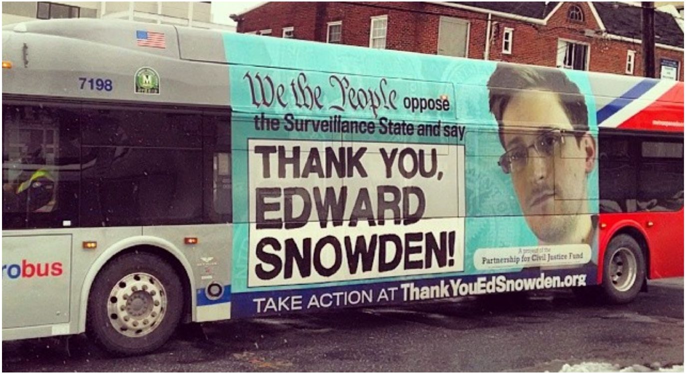
Introduction



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.*

How to keep your private keys secret?

1. Encrypt private key material (e.g. RFC4880: S2K mechanism)
2. Make side-channel attacks difficult
   - Hardware: electromagnetic shielding or tamper-proof HSM
   - Software: constant-time operations on private key material
3. 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`
     `https://git.gitano.org.uk/libgfshare.git/`

     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.

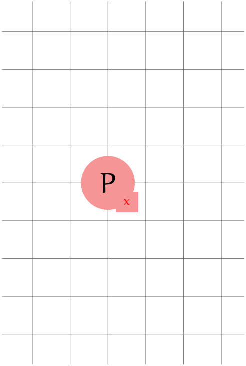
Problems: weak S2K, trusted hardware needed, side-channel issues still possible, no verifiable secret sharing (VSS), combine step

Threshold Cryptography

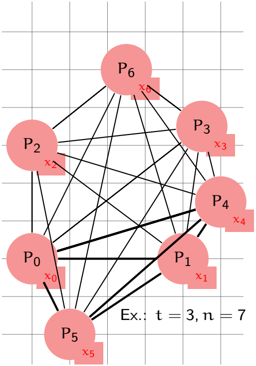
Boyd: *Digital Multisignatures.* Cryptography and Coding, 1986.

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

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

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

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

Threshold Cryptography for OpenPGP [RFC4880]

Basic Case: Each P_i has a shared primary DSA key (for signing) and one [or more] shared ElGamal subkey[s] (for decryption)

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

User ID Packet (tag 13): `Heiko Stamer` ⟨`heikostamer@gmx.net`⟩

Signature Packet (tag 2): version $=$ 4, algo $=$ 17,
created $=$ 1541534836, sigclass $=$ `0x13` (UID Certification), digest algo $=$ 8, ...
key flags $=$ `C|S|0x10`, issuer key ID $=$ `0xDD28EE5AE4783280`, ..., issuer fpr v4

Secret Subkey Packet (tag 7): version $=$ 4, algo $=$ 109,
created $=$ 1504351201, expires $=$ 0,
p, q, g, h, y, n, t, i, QUAL, v_i, C_{ik}, x_i, x'_i

Signature Packet (tag 2): version $=$ 4, algo $=$ 17,
created $=$ 1504351201, sigclass $=$ `0x18` (Subkey Binding), digest algo $=$ 8, ...
key flags $=$ `E|0x10`, issuer key ID $=$ `0xDD28EE5AE4783280`, ...

Corresponding OpenPGP-compatible Public Key

Basic Case: All parties have a common primary DSA key (for verification) and common ElGamal subkey[s] (for encryption)

Public Key Packet (tag 6): version = 4, algo = DSA,
created = 1504351201, expires = 0,
$p, q, g, \widehat{y}$

User ID Packet (tag 13): `Heiko Stamer` ⟨`heikostamer@gmx.net`⟩

Signature Packet (tag 2): version = 4, algo = 17,
created = 1541534836, sigclass = `0x13` (UID Certification), digest algo = 8, ...
key flags = `C|S|0x10`, issuer key ID = `0xDD28EE5AE4783280`, ..., issuer fpr v4

Public Subkey Packet (tag 14): version = 4, algo = ElGamal,
created = 1504351201, expires = 0,
p, g, y

Signature Packet (tag 2): version = 4, algo = 17,
created = 1504351201, sigclass = `0x18` (Subkey Binding), digest algo = 8, ...
key flags = `E|0x10`, issuer key ID = `0xDD28EE5AE4783280`, ...

Threshold Cryptography for OpenPGP [RFC4880]

Sign-Only Case: Each party P_i has a shared primary DSA key

Secret Key Packet (tag 5): version = 4, algo = 108,
created = 1504345345, expires = 31536000,
$p, q, g, h, \hat{y}, n, \hat{t}, i, \widehat{\text{QUAL}}, \hat{C}_{ik}, \text{CAPL}, \hat{x}_i, \hat{x}'_i$

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

Signature Packet (tag 2): version = 4, algo = 17,
created = 1504345345, sigclass = `0x13` (UID Certification), digest algo = 8, ...
key flags = `C|S|0x10`, issuer key ID = ..., ..., issuer fpr v4

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. $2\hat{t} + 1$ of these devices (storing the key shares) must work together to decrypt resp. sign messages

LibTMCG: C++ Classes for Schemes/Protocols

WARNING: Code is still EXPERIMENTAL and SHOULD NOT be used for production!

New-DKG, New-TSch:

`GennaroJareckiKrawczykRabinDKG.cc`

contains ≈ 1.800 LOC

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

`CanettiGennaroJareckiKrawczykRabinASTC.cc`

contains ≈ 4.900 LOC (+900 LOC `PedersenVSS.cc`)

OpenPGP: `CallasDonnerhackeFinneyShawThayerRFC4880.cc`

contains ≈ 16.100 LOC

3rd Party Libraries/Dependencies:

- GNU Multiple Precision Arithmetic Library (`libgmp`) ⩾ 4.2.0
- GNU Crypto Library (`libgcrypt`) ⩾ 1.6.0 (random, crypto primitives)
- GNU Privacy Guard Error Code Library (`libgpg-error`) ⩾ 1.12
- ⋆ Botan: Crypto and TLS for C++11 (`libbotan-2`) ⩾ 2.x (random)

DKGPG: Bunch of Command-Line Programs

WARNING: It's still EXPERIMENTAL and SHOULD NOT be used for production!

Status: β-version 1.1.0 released at 08-Dec-2018, ≈ 21.800 LOC

Dependencies:

- Toolbox for Mental Card Games (`libTMCG`) ⩾ 1.3.16
- GNU Multiple Precision Arithmetic Library (`libgmp`) ⩾ 4.2.0
- GNU Crypto Library (`libgcrypt`) ⩾ 1.6.0
- GNU Privacy Guard Error Code Library (`libgpg-error`) ⩾ 1.12
- zlib Compression Library (`libz`) ⩾ 1.2.3
- ⋆ Library for Data Compression (`libbzip2`) ⩾ 1.0.6

P2P Message Exchange:

- ⋆ CADET service of GNUnet ⩾ 0.11 (not yet released!)
- TCP/IP (e.g. TOR hidden service with port forwarding + `torsocks`)

Runs: Gentoo Linux, Debian GNU/Linux, FreeBSD, OpenBSD

Packages: OpenSuSE, Arch Linux (AUR)

User Interface: Distributed Key Generation

dkg-gencrs generate the domain parameters (p, q, g) of $\mathbb{G}_q$

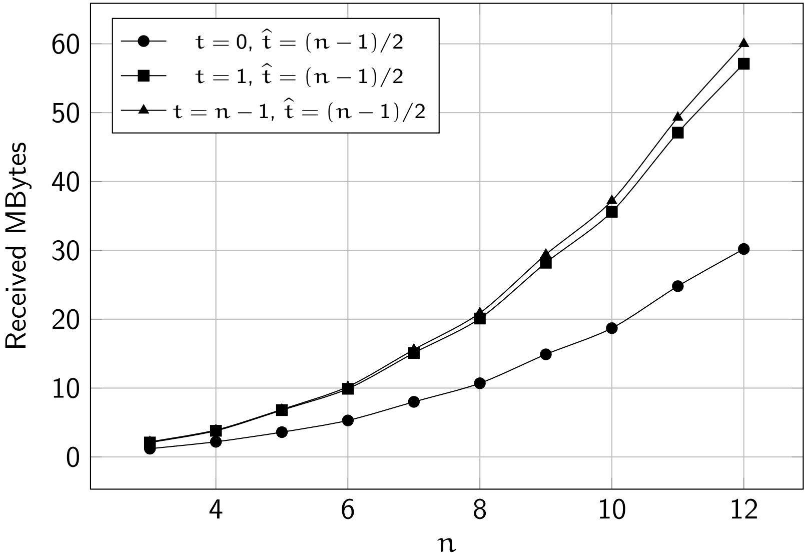
- **-f SEED_{62}** choose parameters according to FIPS 186-4 with SEED

dkg-generate distributed key generation (DSA±ElGamal)

- **-e INTEGER** expiration time of generated key[s] in seconds (default: 0)
- **-g STRING** domain parameters of $\mathbb{G}_q$ ("common reference string")
  default: fixed $\mathbb{G}_q$ with $|p| = 3072$ bit and $|q| = 256$ bit
  (Note that mathematical properties of $\mathbb{G}_q$ reveal DKGPG usage!)
- **-H STRING** hostname of the calling 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)
  default: $(n - 1)/2$
  range: $0, \ldots, (n - 1)/2$, non-shared primary keys by -s 0
- **-t INTEGER** threshold t for New-DKG protocol (encryption scheme)
  default: $(n - 1)/2$
  range: $0, \ldots, (n - 1)$, no encryption subkey by -t 0
- **-w INTEGER** minutes to wait until start of key generation (only GNUnet)
- **-W INTEGER** timeout for point-to-point messages in minutes (default: 5)
- **-y** yet another OpenPGP tool (generate a non-shared key pair)

dkg-addrevoker add external revocation key (cf. RFC 4880)

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



User Interface: Encryption and Decryption

dkg-encrypt message encryption with fixed cipher AES-256

-a INTEGER	enforce use of AEAD algorithm (cf. draft RFC 4880bis)
-b	write output in binary format instead of ASCII-armored
-i FILENAME	read message from a file instead of STDIN
-k FILENAME	keyring containing the required public keys
-o FILENAME	write encrypted output rather to file than STDOUT
-r	select key[s] from given keyring by KEYSPEC
-s STRING	select only encryption-capable subkeys with this fingerprint
-t	throw included key IDs for somewhat improved privacy
-w	allow weak keys

dkg-decrypt message decryption with two operational modes

-b	read input in binary format instead of ASCII-armored
-H STRING	hostname of this peer for TCP/IP (e.g. onion address)
-i FILENAME	read message from a file instead of STDIN
-k FILENAME	verify included signatures based on key[s] from keyring
-K	allow weak keys to verify included signatures
-n	switch to non-interactive mode (using NIZK proofs; ROM)
-o FILENAME	write decrypted output rather to file than STDOUT
-P STRING	password list to encrypt/authenticate TCP/IP connections
-w INTEGER	minutes to wait until start of decryption (only GNUnet)
-W INTEGER	timeout for point-to-point messages in minutes (default: 5)
-y FILENAME	yet another OpenPGP tool (use a non-tElG private key)

User Interface: Generate and Verify Signatures

dkg-verify verification of a single detached signature

-b	read input (i.e. KEYFILE and signature) in binary format
-f TIMESPEC	signature made before given time specification is not valid
-i FILENAME	read signed document from given file (mandatory option)
-k FILENAME	verify signature based on key from keyring instead of KEYFILE determined by issuer (fingerprint) subpacket from signature
-s FILENAME	read detached signature from file instead of STDIN
-t TIMESPEC	signature made after given time specification is not valid
-w	allow weak or expired keys

dkg-sign generation of a (detached) document signature

-C	apply cleartext signature framework (cf. RFC 4880)
-e INTEGER	expiration time of generated signature in seconds (default: 0)
-H STRING	hostname of this peer for TCP/IP (e.g. onion address)
-i FILENAME	read document to sign from given file (mandatory option)
-o FILENAME	write signature rather to file than STDOUT
-P STRING	password list to encrypt/authenticate TCP/IP connections
-t	create a canonical text document signature (cf. RFC 4880)
-U STRING	policy URI tied to generated signature
-w INTEGER	minutes to wait until start of decryption (only GNUnet)
-W INTEGER	timeout for point-to-point messages in minutes (default: 5)
-y FILENAME	yet another OpenPGP tool (use a non-tDSS private key)

User Interface: Miscellaneous Functions (1)

dkg-keysign certification signature generation

- **-1** issuer has not done any verification of the claim of identity
- **-2** issuer has done some casual verification of the claim of identity
- **-3** issuer has done substantial verification of the claim of identity
- **-e INTEGER** expiration time of generated signature in seconds (default: 0)
- **-r** create a certification revocation signature
- **-u STRING** sign only valid user IDs containing this string
- **-U STRING** policy URI tied to generated signature
- **-y FILENAME** yet another OpenPGP tool (use a non-tDSS private key)

dkg-adduid adds another user ID

- **-u STRING** the user ID to add (mandatory option)
- **-y FILENAME** yet another OpenPGP tool (use a non-tDSS private key)

dkg-revuid revokes a specified user ID

- **-u STRING** specifies the user ID to revoke (mandatory option)
- **-y FILENAME** yet another OpenPGP tool (use a non-tDSS private key)

dkg-revoke revocation (certificate) for a key (DSA$\pm$ElGamal)

- **-r INTEGER** reason for revocation (OpenPGP machine-readable code)
- **-R STRING** reason for revocation (human-readable form)

User Interface: Miscellaneous Functions (2)

dkg-keyinfo shows public data of a private key share

-m OLD NEW migrate peer identity (must keep lexicographical order of CAPL)

dkg-keycheck checks a public key for vulnerabilities (e.g. ROCA)

-r check only valid subkeys

dkg-refresh provides 'proactive security' (refresh of key shares)

dkg-timestamp generates a timestamp signature

-a include an OpenPGP notation that represents time deviation
-i FILENAME read the target signature from a file (mandatory option)
-s KEY:VALUE include an OpenPGP notation (e.g. serial number)
-y FILENAME yet another OpenPGP tool (use a non-tDSS private key)

dkg-timestamp-verify verification of a timestamp signature

-b read input (i.e. KEYFILE and signature) in binary format
-f TIMESPEC signature made before given time specification is not valid
-k FILENAME verify signature based on key from keyring instead of KEYFILE
-o FILENAME write the embedded target signature to a file instead of STDOUT
-s FILENAME read timestamp signature from file instead of STDIN
-t TIMESPEC signature made after given time specification is not valid
-w allow weak or expired keys

How can you help?

- Compiling and testing the software on different platforms
- Packaging for more distributions of free operating systems
- Review source code and report vulnerabilities/bugs
- Review design criterias and invent new usage scenarios
  Geer, Yung: *Split-and-Delegate: Threshold Cryptography for the Masses*. International Conference on Financial Cryptography 2002.
- Help with implementation of missing protocols (e.g. RSA, ECC)
- Switch to asynchronous communication model [KG09, KHG12]
- Write standardization draft and advocate for including threshold cryptography in revised RFC 4880bis or other
  NIST Project Threshold Cryptography: draft published, workshop March 2019

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