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(Post Quantum) Signatures in CMS, OpenPGP, and LibrePGP

Work in the scope of Project 480 – "PQC@Thunderbird"

Overview

- Cryptographic Message Formats with Digital Signature:
  - Cryptographic Message Syntax
  - OpenPGP
  - LibrePGP (OpenPGP fork)
- Our work on CMS was done in the scope of Project 480 – “PQC@Thunderbird”
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CMS: Old EUF-CMA Violations

CMS: (generalized) EUF-CMA Problem in Current Proposal for Composite Signatures

OpenPGP: Natural Strong Non-Separability of Composite Signatures

LibrePGP: EUF-CMA Violation through Signature Version Aliasing

OpenPGP: Unsigned Packet Meta Data

Other Aspects of Post Quantum Signatures in Protocols

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EUF-CMA

- EUF-CMA game:
  - adversary can query signing oracle for any message
    - choose $\{m_i\}$
    - receive $\{s_i \mid s_i = \text{sign}(m_i)\}$
  - goal:
    - find valid signature for $m' \neq m_i \forall i$
- Generalization
  - EUF-CMA is restricted to <u>same</u> signature algorithm for <u>query</u> and <u>forgery</u>
  - generalization: allow different signature algorithms

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- sign & encrypt etc. based on X.509 certificates
- protocols building on CMS
  - S/MIME
  - German Smart Metering
  - ...
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SignerInfo Structure

```
 SignerInfo ::= SEQUENCE {
        version CMSVersion,
        sid SignerIdentifier,
        digestAlgorithm DigestAlgorithmIdentifier,
        signedAttrs [0] IMPLICIT SignedAttributes OPTIONAL,
        signatureAlgorithm SignatureAlgorithmIdentifier,
        signature SignatureValue,
        unsignedAttrs [1] IMPLICIT UnsignedAttributes OPTIONAL }

SignedAttributes ::= SET SIZE (1..MAX) OF Attribute


Attribute ::= SEQUENCE {
        attrType OBJECT IDENTIFIER,
        attrValues SET OF AttributeValue }

AttributeValue ::= ANY
```

- signedAttrs:
  - messageDigest attribute:
    - contains Hash(M):

      ```
      messageDigestAttr ::= SEQUENCE {
              attrType OBJECT IDENTIFIER,
              attrValues SET {
                messageDigest OCTET STRING } }
      ```
  - $\mathrm{signedAttr}_M^{\mathrm{DER}} = \mathrm{DER\text{-}encode}(\mathrm{signedAttrs}(M))$
    - to indicate they contain Hash(M)

Attack variant 1: Let the signer sign an attacker-chosen message of specific form w/o signedAttrs:

```
procedure CMS-SIGN( secret key $K_s$, message $M$ )
    if signedAttrs are absent then
        $D = \mathrm{HASH}(M)$
    else
        $D = \mathrm{HASH}(\mathrm{signedAttr}_M^{\mathrm{DER}})$
    end if
    return sign$(K_s, D)$
end procedure
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→ Can forge signatures for arbitrary attacker-chosen message

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procedure CMS-Sign( secret key $K_s$, message $M$ )
    if signedAttrs are absent then
        $D$ = HASH( M' ) // ← cannot be distinguished from this case (remove signedAttrs)
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→ Can forge signatures for message of form $\mathrm{signedAttr}_M^{\mathrm{DER}}$

Format of the signedAttrs when generated by attacker (attack variant 1)

```
31 4b 30 18 06 09 2b 80 40 80 f0 0d 01 09 03 31   // fake OID / attribute
...                                               // further fake content
30 18 06 09 2a 86 48 86 f7 0d 01 09 03 31
0b 06 09 2a 86 48 86 f7 0d 01 07 01 30 2f 06 09
2a 86 48 86 f7 0d 01 09 04 31 22 04 20 e0 be bd
22 81 99 93 42 58 14 86 6b 62 70 1e 29 19 ea 26
f1 37 04 99 c1 03 7b 53 b9 d4 9c 2c 8a
30 ...
```

- fixed
- variable / attacker chosen
- assumption: attacker can make up own OID for unknown attribute [1]
- structure must contain mandatory attributes (messageDigest, contentType)

[1] https://datatracker.ietf.org/doc/html/rfc5652#section-2

Format of the signedAttrs when generated by signer (attack variant 2)

```
31 4b 30 18 06 09 2a 86 48 86 f7 0d 01 09 03 31
0b 06 09 2a 86 48 86 f7 0d 01 07 01 30 2f 06 09
2a 86 48 86 f7 0d 01 09 04 31 22 04 20 e0 be bd  // message digest
22 81 99 93 42 58 14 86 6b 62 70 1e 29 19 ea 26
f1 37 04 99 c1 03 7b 53 b9 d4 9c 2c 8a
```

- fixed (order and set of attributes may still vary, this is not indicated here)
- variable / potentially influenced by attacker

Conceivable vulnerable applications

- directly signing a firmware image
- dense message space (machine-to-machine)
- signing unstructured data – e.g. tokens
- ≈ strongest: external signatures over unstructured secret data with absent content:
    - attacker removes signedAttrs
    - attacker can produces signature over a secret chosen by them

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MTG

- Two signature variants:
  - with signedAttrs (then they are signed)
  - without signedAttrs
- choice of these two variants is **not** protected by signature
- forgeries restricted:
  - either signer has to sign a message in specific format; forged message is arbitrary
  - or the signer has to sign any message; forged signature format is in specific format

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General Countermeasure

- hardened implementations: prohibit messages of the form of signedAttrs
  - during signing
  - and verification
- enforce use of signedAttrs on the application level
  - some protocols already do it
- prohibit the use of signedAttrs
  - would rather be a step backwards
  - modern approch is to use signedAttrs always

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Countermeasures for PQC Algorithms

- PQC Algorithms ML-DSA and SLH-DSA define a context parameter
  - internally, the context is fed to the preprocessing hash
    - h = internal-hash(len(ctx) || ctx || message)
    - then "actually" sign h
  - `ctx=‘‘with_signedAttrs’’`
  - `ctx=‘‘without_signedAttrs’’`
- context achieves domain separation
  - between signing w/ and w/o signedAttrs
  - can be extended to other uses ...
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Other Aspects of Post Quantum Signatures in Protocols

Hybrid / Multi-Algorithm Signatures

- insufficient trust in ML-DSA
- general recommendation: Multi-Algorithm Signatures
    - $s_1 = \text{sign-ECDSA}(m)$
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    - $s = s_1 || s_2$

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Protection against Signature Stripping Attacks

- Signature stripping attack:
  - Adversary removes one of the two signatures
  - → Standalone signature
  - with simple parallel signatures, this has no security implications
    - no change of message
    - verifier must always accept only secure signatures
    - verification at later point can be affected (availability)
- requires key-reuse
  - ECDSA-🔑$_1$ → ECDSA-standalone 📜 $_1$
  - ECDSA-🔑$_1$ → ML-DSA+ECDSA 📜 $_2$
  - **not** allowed by draft-ietf-lamps-pq-composite-sigs-03

EUF-CMA Problem in Current Proposal for Composite Signatures

- draft-ietf-lamps-pq-composite-sigs-03
- relevant for ML-DSA+X
- `Composite-ML-DSA.Sign (sk, M, ctx)`

```
M’ = OID || len(ctx) || ctx || M
mldsaSig = ML-DSA.Sign( key=mldsaSK, msg=M’, ctx=OID )
tradSig = Trad.Sign( tradSK, M’ )
```

- Aim of countermeasure: achieve Weak-Non-Separability
  - Leaves "artifact" in the message
  - ϟ Artifact is violation of (generalized) EUF-CMA
    - generalized because cross-algorithm CMA is needed
- (generalized) EUF-CMA forgeries
  - remove PQ part from "ML-DSA+ECDSA" signature
  - ECDSA signature valid
  - forged message: `OID` || `len(ctx)` || `ctx` || `M`

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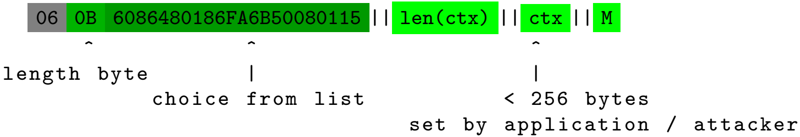
Forged Message

- forged message: `OID || len(ctx) || ctx || M`
- OID: predefined list, but variable content



```
  06 0B 6086480186FA6B50080115 || len(ctx) || ctx || M
      ^           ^                    ^
length byte       |                    |
           choice from list          < 256 bytes
                          set by application / attacker
```

- protocols with valid messages starting with 06 potentially affected

Countermeasure

- Countermeasure: detectable constant prefix

  `<32 magic bytes> 06 0B 6086480186FA6B50080115 || len(ctx) || ctx || M`

- newer implementations can check for the magic bytes → attack detection

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Non-Separability in OpenPGP Signatures

v6 signature packet

v6 = 0x06
sig-type 0x00
1B pk-algo = hybrid-. . .
1B hash-algo
2B hashed subpacket length
hashed subpackets
2B unhashed subpacket length
unhashed subpackets
2B checksum for hash-value
algorithm-specific signature data

sig 1

sig 2

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v6 signature packet

hashed as meta data

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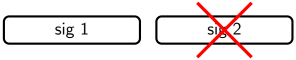

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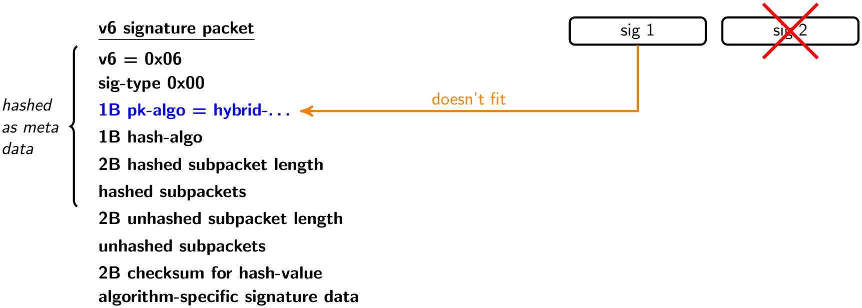

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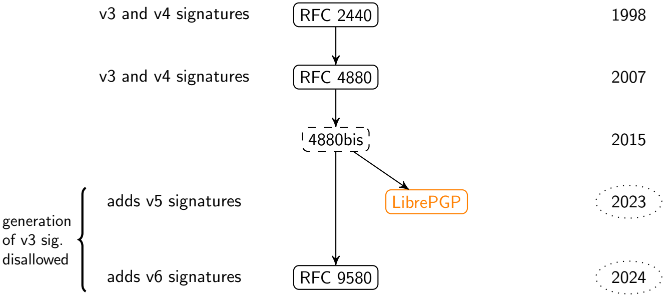
v3 and v4 signatures
RFC 2440
1998
v3 and v4 signatures
RFC 4880
2007
4880bis
2015
adds v5 signatures
LibrePGP
2023
generation of v3 sig. disallowed
adds v6 signatures
RFC 9580
2024

LibrePGP v5 Signatures

v5 signature packet

v5 = 0x05

sig-type 0x00 *// document signature*

1B pk-algo

1B hash-algo

2B hashed subpacket length

hashed subpackets

2B unhashed subpacket length

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LibrePGP v5 - v3 Signature Aliasing

- Signature aliasing:
  - hashed data is ambiguous
  - → multiple “interpretations” of what was signed
- requirement:
  - injective / one-to-one mapping of protocol semantics to hashed data
  - “semantics → hashed data”: always given
  - “semantics ← hashed data”: not necessarily
    - hashed data needs to be uniquely parseable
    - from front, rear, or both
- example: hash first and last name together:
  - maxi + müller → maximüller
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LibrePGP v5 - v3 Signatures Aliasing

hashed data for a v5 document signature	hashed data for a v3 document signature
document data	document data
v5 = 0x05	v5 = 0x05
sig-type 0x00	sig-type 0x00
1B pk-algo	pk-algo
1B hash-algo	hash-algo
2B hashed subp len	2B hashed subp len
hashed subpackets	hashed subpackets
1B content format	1B content format
1B length || file name	1B length || file name
4B date	4B date
v5 || 0xFF	v5 || 0xFF
hashed-len 8 = 0x00	hashed-len 8 = 0x00
hashed-len 7 = 0x00	hashed-len 7 = 0x00
hashed-len 6 = 0x00	hashed-len 6 = 0x00
hashed-len 5 = 0x00 or 0x01	**sig-type = 0x00 or 0x01**
4B hashed-len 1-4 ≥ 0	**4B sig. creation date**

LibrePGP v5 - v3 Signatures Aliasing

hashed data for a v5 document signature		**hashed data for a v3 document signature**
document data ←	*validly signed document*	→ document data
v5 = 0x05		v5 = 0x05
sig-type 0x00		sig-type 0x00
1B pk-algo		pk-algo
1B hash-algo		hash-algo
2B hashed subp len		2B hashed subp len
hashed subpackets		hashed subpackets
1B content format		1B content format
1B length || file name		1B length || file name
4B date		4B date
v5 || 0xFF		v5 || 0xFF
hashed-len 8 = 0x00		hashed-len 8 = 0x00
hashed-len 7 = 0x00		hashed-len 7 = 0x00
hashed-len 6 = 0x00		hashed-len 6 = 0x00
hashed-len 5 = 0x00 or 0x01		**sig-type = 0x00 or 0x01**
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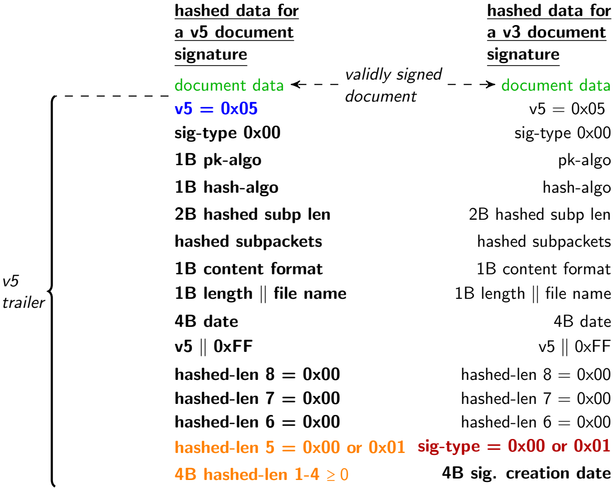

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hashed-len 5 = 0x00 or 0x01		sig-type = 0x00 or 0x01
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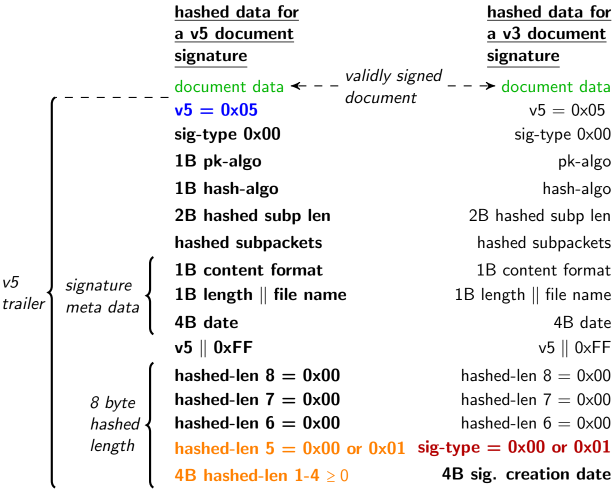
		document data	← – – *validly signed document* – – →	document data
v5 trailer		**v5 = 0x05**		v5 = 0x05
		sig-type 0x00		sig-type 0x00
		1B pk-algo		pk-algo
		1B hash-algo		hash-algo
		2B hashed subp len		2B hashed subp len
		hashed subpackets		hashed subpackets
	signature meta data	**1B content format**		1B content format
		1B length ‖ file name		1B length ‖ file name
		4B date		4B date
		v5 ‖ 0xFF		v5 ‖ 0xFF
		hashed-len 8 = 0x00		hashed-len 8 = 0x00
		hashed-len 7 = 0x00		hashed-len 7 = 0x00
		hashed-len 6 = 0x00		hashed-len 6 = 0x00
		hashed-len 5 = 0x00 or 0x01		**sig-type = 0x00 or 0x01**
		4B hashed-len 1-4 ≥ 0		**4B sig. creation date**

LibrePGP v5 - v3 Signatures Aliasing



		hashed data for a v5 document signature		**hashed data for a v3 document signature**
		document data	← validly signed document →	document data
v5 trailer		**v5 = 0x05**		v5 = 0x05
		sig-type 0x00		sig-type 0x00
		1B pk-algo		pk-algo
		1B hash-algo		hash-algo
		2B hashed subp len		2B hashed subp len
		hashed subpackets		hashed subpackets
	signature meta data	**1B content format**		1B content format
		1B length ‖ file name		1B length ‖ file name
		4B date		4B date
		v5 ‖ 0xFF		v5 ‖ 0xFF
	8 byte hashed length	**hashed-len 8 = 0x00**		hashed-len 8 = 0x00
		hashed-len 7 = 0x00		hashed-len 7 = 0x00
		hashed-len 6 = 0x00		hashed-len 6 = 0x00
		hashed-len 5 = 0x00 or 0x01		**sig-type = 0x00 or 0x01**
		4B hashed-len 1-4 ≥ 0		**4B sig. creation date**

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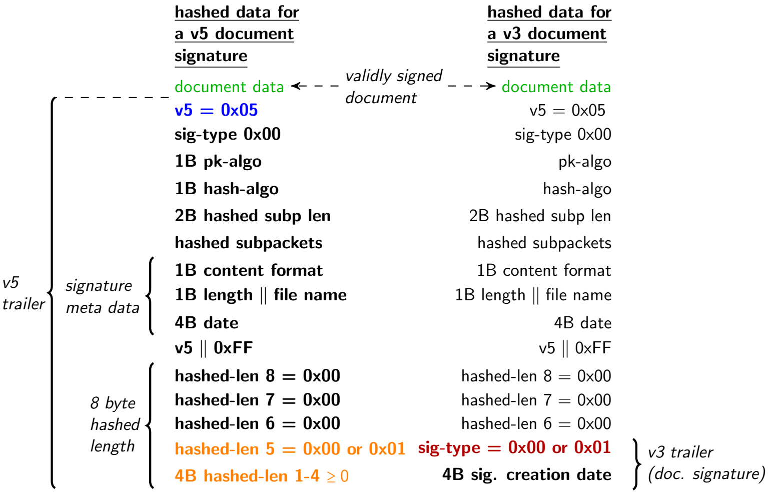

		hashed data for a v5 document signature		**hashed data for a v3 document signature**	
		document data	*validly signed document*	document data	
v5 trailer		**v5 = 0x05**		v5 = 0x05	
		sig-type 0x00		sig-type 0x00	
		1B pk-algo		pk-algo	
		1B hash-algo		hash-algo	
		2B hashed subp len		2B hashed subp len	
		hashed subpackets		hashed subpackets	
	signature meta data	**1B content format**		1B content format	
		1B length || file name		1B length || file name	
		4B date		4B date	
		v5 || 0xFF		v5 || 0xFF	
	8 byte hashed length	**hashed-len 8 = 0x00**		hashed-len 8 = 0x00	
		hashed-len 7 = 0x00		hashed-len 7 = 0x00	
		hashed-len 6 = 0x00		hashed-len 6 = 0x00	
		hashed-len 5 = 0x00 or 0x01		**sig-type = 0x00 or 0x01**	*v3 trailer (doc. signature)*
		4B hashed-len 1-4 ≥ 0		**4B sig. creation date**	

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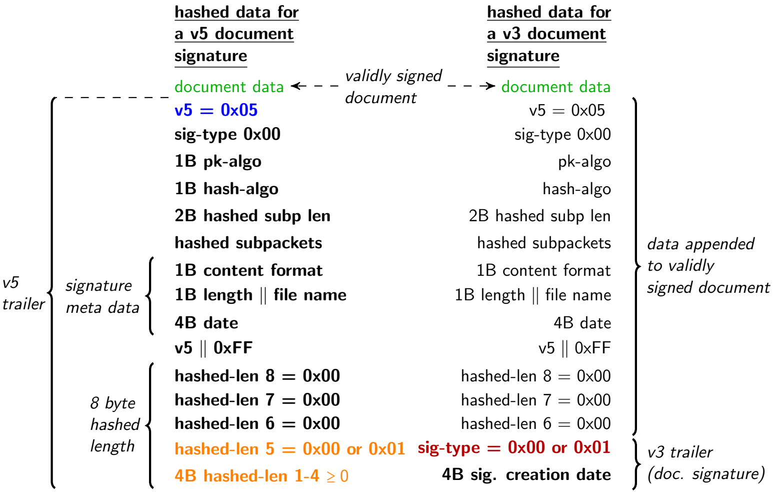

		hashed data for a v5 document signature		hashed data for a v3 document signature	
		document data	validly signed document	document data	
v5 trailer		**v5 = 0x05**		v5 = 0x05	*data appended to validly signed document*
		sig-type 0x00		sig-type 0x00	
		1B pk-algo		pk-algo	
		1B hash-algo		hash-algo	
		2B hashed subp len		2B hashed subp len	
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	signature meta data	**1B content format**		1B content format	
		1B length ‖ file name		1B length ‖ file name	
		4B date		4B date	
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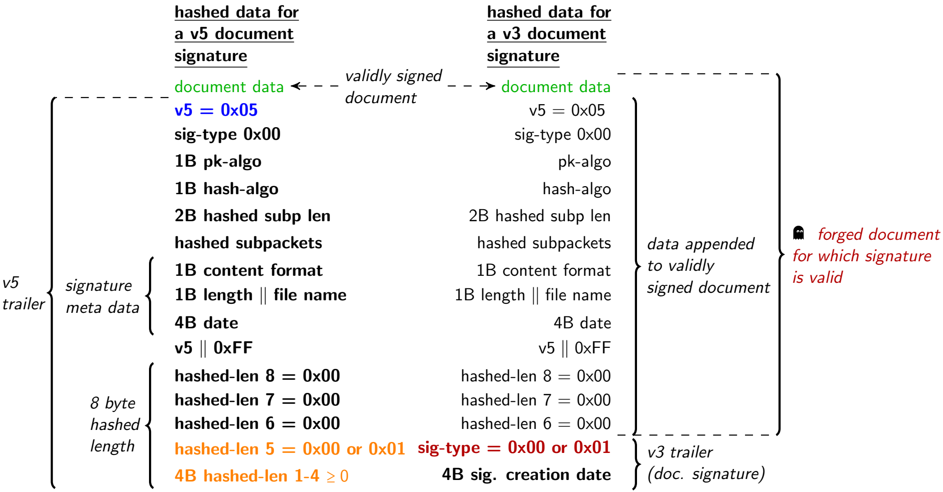

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validly signed document
v5 trailer
signature meta data
8 byte hashed length
data appended to validly signed document
v3 trailer (doc. signature)
👻 *forged document for which signature is valid*

LibrePGP v5 - v3 Signatures Aliasing

- v5 → v3 aliasing possible
  - v3 signatures may still be verified
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v4:	...	...	...	...	**hashed-subp bd**	0x04	0xFF	4B hashed length
v6:	...	...	...	...	**hashed-subp bd**	0x06	0xFF	4B hashed length
v5:	...	0x05	0x0FF	hl8	hl7	hl6	$\underbrace{\text{hl5}}_{0 \text{ or } 1}$	low 4B of hashed len.

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CMS: (generalized) EUF-CMA Problem in Current Proposal for Composite Signatures

OpenPGP: Natural Strong Non-Separability of Composite Signatures

LibrePGP: EUF-CMA Violation through Signature Version Aliasing

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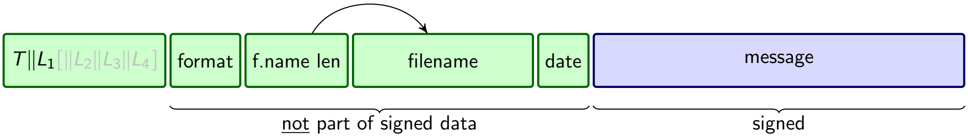

$T||L_1[||L_2||L_3||L_4]$

format

f.name len

filename

date

message

not part of signed data

signed

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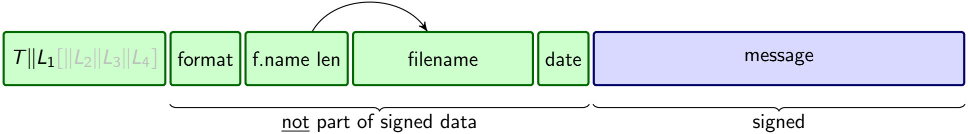

- LibrePGP: header added to signed data for v5 signatures

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SLH-DSA Design

MTG

- choice
  - opt_rand ← rnd
  - opt_rand ← PK.seed
- $R \leftarrow \mathrm{PRF}_{\mathrm{msg}}(SK.prf, \mathrm{opt\_rand}, \mathrm{PK.root}, M)$ *// M to hedge against RNG failure*
- $\mathrm{digest} \leftarrow H_{\mathrm{msg}}(R, \mathrm{PK.seed}, \mathrm{PK.root}, M)$ *// improved collision resistance*
- compute signature based on *digest* . . .

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⟶ no increased collision resistance at all

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- OpenPGP: bound to hash-then-sign
  - compute hash
  - sign the digest with “pure” variant (current proposal)
  - → no two-pass-problem with SLH-DSA
- RFC 9580: v6 signatures
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    - this attack requires finding 2nd preimage
    - "fixes" the pre-hash hash algorithm with the strength of the internal hash
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    - compute hash in the application
    - provide hash value to the signature function
- pre-hash variant ensures:
    - domain separation from pure variant
    - prevents digest substitution attacks
        - this attack requires finding 2nd preimage
        - “fixes” the pre-hash hash algorithm with the strength of the internal hash
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Thank you for your attention

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